D-HYDRO flood simulations for waterboard Noorderzijlvest

Waterschap Noorderzijlvest

Date	January 2021
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Preface

I have written this report as part of the bachelor's thesis for my study Civil Engineering at the University of Twente. I have researched how D-HYDRO can be used best for flood modelling for waterboard Noorderzijlvest. I analysed the influence of different model components on both the model output and computation time. I also compared results of D-HYDRO simulations to results of TYGRON simulations. This research is commissioned by the waterboard Noorderzijlvest.

I want to thank everyone from the waterboard who has helped me with my research. In special I want to thank Vincent de Looij for helping me with staying involved with the waterboard despite all the COVID-19 regulations. I also want to thank Vasilis Kitsikoudis as my supervisor for his great feedback and always being ready to help me when necessary.

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Scherpenzeel (FR), 20-01-2021

Abstract

Within this research, 2D flood simulations in D-HYDRO have been performed and analysed. This is done to give an advice to the waterboard on how to use 2D flood simulations in D-HYDRO. It is important that these simulations can be set up quickly, since flood simulations are needed urgently when the water level reaches alarming levels. D-HYDRO is a new software package being developed by Deltares. The D-FLOW FM module of the software package allows for the 1D, 2D or 3D simulations of water flow. D-HYDRO simulations are compared to each other within a sensitivity analysis, to analyse how different modifications to the model affect model output and computation time. Also, D-HYDRO and TYGRON simulations have been compared, in order to see how different D-HYDRO models perform compared to TYGRON.

The sensitivity analysis resulted in an advice for how different model components should be used when making a flood simulation. The tested model components are grid size, flexible mesh, culverts, roughness values, precipitation, wind, dams, model size, initial water level, and breach inflow. Within this report, for each of these components, an advice is given on how to use them within flood models. This advice is based on both the effect on model output, computation time and model set up time.

The comparison between D-HYDRO and TYGRON has shown similar inundation patterns for both software packages. However, there are local differences in flood propagation between the simulations that are performed. These differences can mainly be related back to the known differences between the simulations. The most important difference being that TYGRON uses a fine grid with grid cell sizes of 1*1 meter, while D-HYDRO used 10*10 meter grid cells. Despite this big difference, the results were still similar for the cases that have been tested. Even when performing simulations with even bigger grid cells (up to 100*100 meter), D-HYDRO has shown promising results. With the large grid cells, the computation shortens significantly. A simulation that takes 71 hours at 10*10 meters, takes only 2 minutes at 100*100 meters. This comes with a loss in accuracy, but the overall inundated area is similar for both simulations.

From this research it can be concluded that 2D D-HYDRO flood simulations are promising for the waterboard. When using large grid cells, results can be gathered quickly. Flexible mesh allows important areas to have a more detailed grid, and thus a more detailed simulations, while less important areas have less details. This has proven to be a good tool to remain accurate while saving on computation time. Furthermore, models can be set up with a small amount of data, and additional data can be used for additional accuracy. This can all be done within an intuitive user interface, that is relatively easy to learn. With some training of employees and modifications to the database, the waterboard can use D-HYDRO for 2D flood simulations.

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1. Introduction

1.1. Background information

To successfully manage water, it is important to be able to make accurate predictions of future events. Within flood management, future events cannot be tested since such events can have disastrous results. Therefore, simulations are crucial in this research field. An example situation that shows the necessity of flood simulations for the waterboard of Noorderzijlvest occurred in 2012. High water levels in the Eemskanaal in the north of the Netherlands opposed a threat to inhabitants living near the channel. There was a flood hazard and the policy team stated: “the dike could fail, which could lead to an area of hundreds of hectares being flooded.” At the time, 800 people have been evacuated from the village called Woltersum (RTL Nieuws, 2012). Because of the high water levels, meadows were inundated by ground water. Within the dike at the Eemskanaal, piping occurred (Haasjes, 2012). Piping can lead to dike breaches, however luckily, this did not happen in 2012. Situations like this show the necessity of a good preparation against flooding. And with good preparation, better decisions can be made at the time of a flooding.

To adequately handle crisis situations, the waterboard Noorderzijlvest has a crisis management organisation. The crisis organisation is a scalable team. In case of a hazard, specialised teams are called upon. Depending on the situation, the amount of people that join the crisis organisation can vary. The crisis management teams are not limited to the waterboard staff. Emergency services, other waterboards, provinces, and municipalities, can all work together in case of a crisis (de Graaf, 2016).

When there is the threat of a dike breach, flood simulations can play a valuable role to assess the risks. To decide upon further actions, information is required about what areas are prone to flooding for a specific situation. These further actions could be laying sandbags, protecting valuable areas, or evacuation of people or cattle.

In general, risk can be expressed as the product of probability of occurrence and the consequence of a certain event (Bouma, 2005). The usage of flood modelling helps to get a better understanding of the possible consequences of a certain event. With a flood model, physical properties of the flooding can be predicted for the area. Examples of these physical properties are water levels and flow velocities. With the help of these physical properties, a prediction for the flood damage can be made. Flood damage can be divided into three categories: losses in human life (social damage), damage to environment (environmental damage), and damage to property (economic damage) (Zeleňáková et al., 2020). However, calculating these damages is not straightforward since it can depend on many factors.

Floods do not occur out of nowhere. In 2012, high water levels were recorded, which caused an alarming situation for the dikes. This gives some time to prepare for situations like this. Within this time, flood modelling can be valuable to calculate the possible effects of floods. However, models that are made before a dike breach happens, generally have a large uncertainty since the dike breach size and location are unknown. This uncertainty comes along with the usual uncertainties of a hydrological model, which are structural errors in a model, model parameter uncertainties and data errors (Liu & Gupta, 2007).

At the event of an actual dike breach, decision makers want to have information about the risks related to the dike breach as quickly as possible. At this time, more is known about the dike breach location and size, and flood modelling can provide a more accurate prediction which areas are prone to flooding since more data is available. Flood models that are used must be set up and run quickly, as the decision makers want to decide on further action as soon as possible. Ideally, flood models have already been made and run beforehand. With the information provided by the model, decisions can be substantiated with data.

1.2. Thesis outline

In chapter 2 of this report, the problem definition for this research is stated. In chapter 3, the theoretical knowledge regarding this research is discussed and explained. In chapter 4, the methodology for this research is explained. In chapter 5, the results of performed simulations are discussed. Chapter 5 is divided in 3 parts. In chapter 5.1 and chapter 5.2 it is analysed how different model components affect model output based on the output of the performed simulations. In chapter 5.3, multiple D-HYDRO simulations are compared to TYGRON simulations. In chapter 6, there is a discussion about the results of this research. In chapter 7, the conclusions and recommendations based on the research are given. The appendices provide additional information.

2. Problem definition

The waterboard of Noorderzijlvest is investigating the possibilities of using the D-HYDRO software package. The D-HYDRO package is currently the most interesting option, since it has a broad variety of modelling possibilities. However, D-HYDRO is still in a beta stage, and there is little experience with the software. Therefore, the waterboard wants to gain knowledge about how the software is used, and how it can be applied to the problems of Noorderzijlvest. The focus for this research is on flood modelling. The waterboard wants to know about how D-HYDRO can be used most effectively for flood modelling.

This research is focused on 2D flood simulations within D-HYDRO. 2D simulations are useful for flood modelling since water can flow freely through an area, without being limited to predefined flow routes like in 1D modelling. Also, 2D simulations have lower computation times than 3D models, with computation time being an important factor in case of a flooding. More about 2D flood models can be read in chapter 3.

In addition to testing how the software can be used most effectively, also the results of D-HYDRO models are compared to results from a 2019 model study from the waterboard. In this study, TYGRON has been used to simulate dike breaches throughout the management area of waterboard Noorderzijlvest. This study has been performed in 2019 for a climate stress test. TYGRON is a competitor of D-HYDRO within flood simulations. The main feature of TYGRON is fast computation since models are run on a supercomputer.

Research purpose

D-HYDRO is a new software package. Therefore, there has not been a lot of research on the performance of the complete package. The D-FLOW FM module used in this study, has been studied in other research. Examples of conducted research are: The comparison between D-FLOW FM and MIKE 21 FM (Symonds, et al., 2016), the comparison between D-FLOW FM and WAQUA, with an additional focus on the Flexible Mesh (Ten Hagen et al., 2014), and research focused on flexible mesh performance (Hoch et al., 2018). In general, research done on D-FLOW FM is mainly focused on the comparison to other software, and on testing the effectiveness of flexible mesh.

This research will help in gaining more knowledge about the applications of D-HYDRO for flood modelling. This is achieved by providing insight in the relation between computation time, model accuracy, and the model set up. Also, the results from models used in the study are compared to earlier performed simulations with TYGRON, in order to validate results.

3. Theoretical framework

3.1. D-HYDRO

The D-HYDRO software package can simulate tsunamis, storm surges, sediment transport, waves, water levels and river morphology. Also, the interaction between these processes can be simulated. All of these can be done within the GUI, that allows to build complex models. Results can be visualised and exported to Google Earth via Python scripting. The software package of D-HYDRO contains different modules for different goals. All these modules can be easily combined.

Within D-HYDRO, 1D, 2D and 3D modelling is possible. Also, D-FLOW Flexible mesh (the main module of D-HYDRO) allows for more efficient calculations. Grid cells are not of fixed size or shape, but they can be differed based on what the environment requires. For example, dikes can be represented in a high-resolution grid with a lot of detail, while on a flat pasture a low resolution can be used. Because of this, the model uses the computers computational power more efficiently. Less calculation power is used for simple terrain, while more computation power is used for detailed structures. This results in a more detailed simulation, with less computation time.

To give an indication of what D-HYDRO is capable of, the different modules of the software package are listed: D-Waves is used for calculating wave propagation, on unequal bottoms. D-Real Time Control makes simulations that show how current infrastructure can be used more efficiently. It optimises a system reaction to water levels, rainfall, and other factors. D-Water Quality simulates water and sediment transport. D-Particle Tracking describes the spatial distribution of concentrations of individual particles. D-Morphology calculates sediment transport and morphological changes. For this research, the D-FLOW Flexible Mesh (D-FLOW FM) module is used.

3.2. TYGRON

The TYGRON Geodesign Platform offers a solution to a wide range of engineering problems, such as flooding, droughts, heatwaves, energy, housing development, infrastructure, liveability, and economy. TYGRON is used by multiple waterboards and consultancies. The TYGRON design platform has had more than 10.000 projects in 15 countries. In 2019, the waterboard has performed multiple flood simulations in TYGRON. These simulations are used to compare TYGRON and D-HYDRO in this research.

One part of TYGRON's design platform is the water module. This provides simulations of the movement of water and the impact on the project area. This water module is primarily created for the analysis of spatial water problems in urban and rural areas. This includes heavy precipitation scenarios and flooding evacuation scenarios. Flood simulations made in TYGRON have been tested against multiple UK Benchmarks (TYGRON, 2019). In all these tests, TYGRON simulated similar output to the other tested models.

The water module of TYGRON is a 2D grid model, based on Saint Venant equations. An important part of TYGRON's accurate and fast simulations, is that computations are executed on high performance GPU servers. More information about how hardware affects computation time can be read in Appendix A: Model computation time.

3.3. Hydraulic models

The flow of water in rivers is studied with specialized modelling, the so-called hydraulic modelling. Hydraulic models can be classified based on their degree of complexity. One dimensional models calculate hydraulic characteristics for certain cross sections. One of the advantages of 1D models is a low computation time. The disadvantage is that only data along the cross sections is calculated. This can be sufficient for a river, however in case of a flooding, water goes outside the river. This makes 1D models less useful for calculations outside of the riverbed (Wicks, 2015).

Two dimensional models consist of a map of different grid cells. Each of these grid cells has its own characteristics and status. The grid cells interact with each other to reproduce what would happen in the real world. Two dimensional models are more flexible than 1D models since no predefined flow routes are used. The disadvantage is that 2D models can have a large computation time, especially when the resolution is high (Wicks, 2015).

Three dimensional models are similar to 2D models, except in that they have an extra dimension, the depth. 2D models have just a 2D grid system, 3D models have a 3D space system. This is more sophisticated than 2D, but also requires more computation time, and can be more difficult to set up (Dahm et al., 2014).

1D, 2D and 3D modelling can also be combined. Using the advantages of both models, 1D2D models have the general accuracy of a 2D model, but for specific point features or flow channels, they use 1D models. This increases the speed of the overall model, and still maintains the accuracy and freedom that a 2D model provides. The same can be done for 1D3D models (Dahm, Hsu, Lien, Chang, & Prinsen, 2014).

3.4. 2D simulations in D-FLOW FM

For this study, 2D models are analysed. 2D simulations are good for flood modelling since water can flow freely through an area, without being limited to predefined flow routes like in 1D modelling. Also, 2D simulations have lower computation times than 3D models, with computation time being an important factor in case of a flood. 1D2D models are also excellent for flood modelling, but unfortunately due to some problems with the current beta release of D-HYDRO, they have not been further analysed for this research.

The basis for a 2D hydraulic model is a 2D grid representation of the real world. D-FLOW FM allows for both structured (mesh from uniform pattern) and unstructured grids (no uniform pattern) to be used. This makes it possible to use a flexible mesh. A flexible mesh is a grid with a varying grid cells size and shape. The grid can be refined at certain locations, which provides extra details at the refined locations. This allows for an accurate representation of the real world at critical areas in the simulation (e.g., waterways), and it saves computation time by having a less detailed representation of areas that are not as important to the simulation, for example meadows. An example of a flexible mesh can be seen in Figure 1.

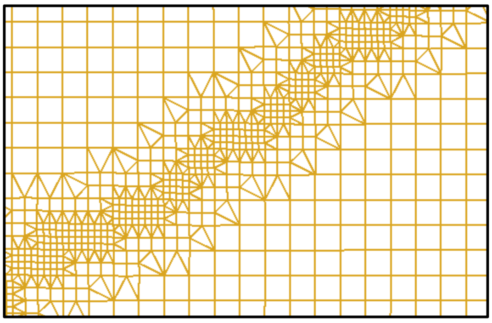


Figure 1: On the left an example of flexible mesh, a 20 meter grid can be refined to a 5 meter grid at specified locations. On the right the satellite view of this location.

Within the construction of a grid, there are 2 important properties that define the quality of the grid, the smoothness, and the orthogonality. The grid smoothness ratio is the ratio between the size of two adjacent cells. Ideally, this ratio is 1, meaning both grid cells are of equal size. The orthogonality defines the angle between the flow link and the net link (Figure 2). Ideally, this angle is 90 degrees.

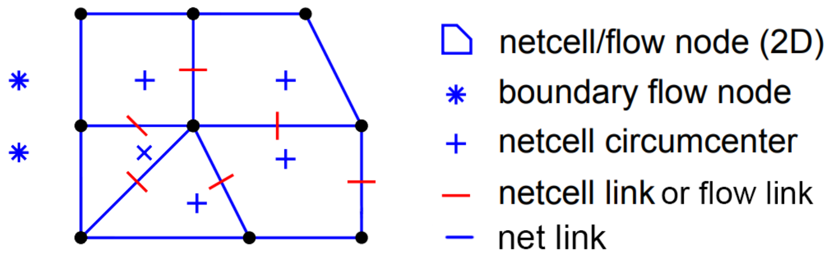


Figure 2: Representation of grid cells in D-HYDRO (Deltares, 2020b)

When a grid has been constructed, height data from a digital elevation maps (DEM) is added. From the height data provided by such maps, D-HYDRO determines the bathymetry of the area. The waterboard provides multiple DEM's, with 5-meter, and 0.5-meter resolution. More about the input data can be read in Appendix B: Input.

The size of the grid cells used in D-HYDRO can be chosen by the user. With larger grid cells, simulations can be done quickly. However, by using large grid cells, details of the terrain are lost. As an example, on a 20-meter grid size, a 5-meter water channel can get averaged out with the surrounding landscape. Even though this water channel has a significant impact on how water flows within the region.

From the grid representation of the area, D-FLOW FM can calculate the flow of water through the system. To do this, D-HYDRO solves the depth averaged continuity equation, derived by the continuity equation for incompressible fluids ($\nabla \cdot \mathrm{u} = 0$).

$$\frac{\partial h}{\partial t} + \frac{\partial Uh}{\partial x} + \frac{\partial Vh}{\partial y} = Q \tag{1}$$

With h being the water depth (m), U and V being the depth average velocity components (m/s), and Q being the contribution per unit area due to discharge, precipitation, and evaporation. Q can be calculated according to equation 2.

$$\mathrm{Q} = \int_0^h (q_{in} - q_{out})dz + P - E \tag{2}$$

With Q being the contributions per area unit of discharge or withdrawal of water (m/s), h as water depth (m), q_{in} and q_{out} being the local sources or sinks of water (1/s), P the non-local source term of precipitation (m/s) , and E the non-local sink term of evaporation (m/s). (Deltares, 2019a)

Besides the continuity equation, D-HYDRO also solves the momentum equation in the x and y direction.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} + fv = \frac{1}{\rho_0} * \frac{\partial P}{\partial x} + F_x + \frac{\partial}{\partial z}\left(V_v \frac{\partial u}{\partial z}\right) + M_x \tag{3}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu = \frac{1}{\rho_0} * \frac{\partial P}{\partial y} + F_y + \frac{\partial}{\partial z}\left(V_v \frac{\partial v}{\partial z}\right) + M_y \tag{4}$$

With:

u = Velocity in x direction (m/s) | v = Velocity in y direction (m/s)
w = vertical velocity (m/s) | z = water depth (m)
f = Coriolis parameter (1/s) | ρ_0 = Density of water (kg/m^3)
P = Pressure (kg/(m*s^2)) | V_v = vertical eddy coefficient (m^2/s)
F_x and F_y = Forces that represent the unbalance of horizontal Reynold stresses (m/s^2)
M_x and M_y = Contribution to momentum from external forces in the x and y direction (m/s^2)

Calculations are done at every timestep, for the entire grid. The amount of grid cells and the time step have a big influence on the computation time. The time step is determined by the Courant condition (CFL). This number describes the amount of grid cells that a particle of water can travel during a timestep. With higher velocities, or with smaller grid cells, the time step must be shorter. The time step must be shorter because with a longer time step, the water would flow further than one cell within the time step.

3.5. Project concepts

Within this project, certain terms or phrases will be used frequently. In Table 1, the definitions as used in this report, are stated.

Table 1: Project terms and a description of the definition within this research report.

Term	Definition
Computation time	The time it takes for a model to run.
Set up time	The time it takes for an experienced user to set up a model.
DEM	The digital elevation map of the area.
Grid	The computational grid used for calculations in D-HYDRO.
Grid cell size	The size of a single cell within a grid.
Grid resolution	How fine the grid is, a high resolution means a small grid cell size. A low resolution means a large grid cell size.
Flexible mesh	A grid that has a varying grid size based on the location; the user can define where a more detailed grid is required.
Refinement	With flexible mesh, the base grid can be refined at specific locations. This creates different grid sizes for different locations. For example, a 20*20 meter grid cell can be refined to four 10*10 meter grid cells. This is one refinement. A second refinement would mean dividing the four 10*10 meter grid cells to 16 5*5 meter grid cells.
Breach inflow	The discharge through a dike breach.

4. Research questions

The main research question for the thesis is: **How can the software suite D-HYDRO be used most effectively to model a dike breach fast and accurately, and thereby contribute to flood management for the waterboard?**

Three sub questions have been set up that aid to answer the main research question. These are:

1. How do different model components affect the accuracy of the output of a D-HYDRO model?
2. How do different model components affect the computation time of a D-HYDRO model?
3. How do D-HYDRO simulations compare to earlier performed simulations in TYGRON?

4.1. Methodology

To answer research question 1 and 2, a sensitivity analysis has been conducted. The sensitivity analysis is divided into two parts.

The first part of the sensitivity analysis is focused on fundamental model components, and how these components affect the output and set up time of a model. These components are grid size, time step, and the digital elevation map. Different grid sizes, time steps, and elevation maps are tested, and the resulting inundations and computation times are compared to each other. These tests function as the basis for all the other simulations that have been performed for this study.

The second part of the sensitivity analysis is focused on finding the effects of including additional data to the model. The starting model is a simple 2D 5*5 meter resolution model with only a DEM of the area and a dike breach inflow. In every test, different additional input data are added to this model such as culverts, precipitation, and wind, to see the effects on both the output and computation time.

With the results of this sensitivity analysis, both research questions 1 and 2 can be answered.

To answer research question 3, specific situations that have previously been modelled in TYGRON, are re made in D-HYDRO. There are some limitations to this, since there are some unknown factors in the TYGRON simulation, and only images of final results after 4 days are available. The results of the D-HYDRO models are compared to the results of the simulation in TYGRON. The conclusion of this comparison is the answer to research question 3.

Combining the knowledge gained by answering research questions 1, 2, and 3, the main research question can be answered.

4.2. Study areas

For the sensitivity analysis, the main focus is on the Eemskanaal. The Eemskanaal can be seen in Figure 3. Figure 3 also shows the DEM of the area near the Eemskanaal, and the three selected study areas. All figures in this report have the same orientation, with the north at the top, therefore the north arrow is not mentioned in the other figures. This study area has been chosen for the sensitivity analysis, since the potential inundated area is small and predictable because of the geography of the area. The small area is beneficial for a shorter computation time, which is desirable since the study must be completed within 10 weeks.

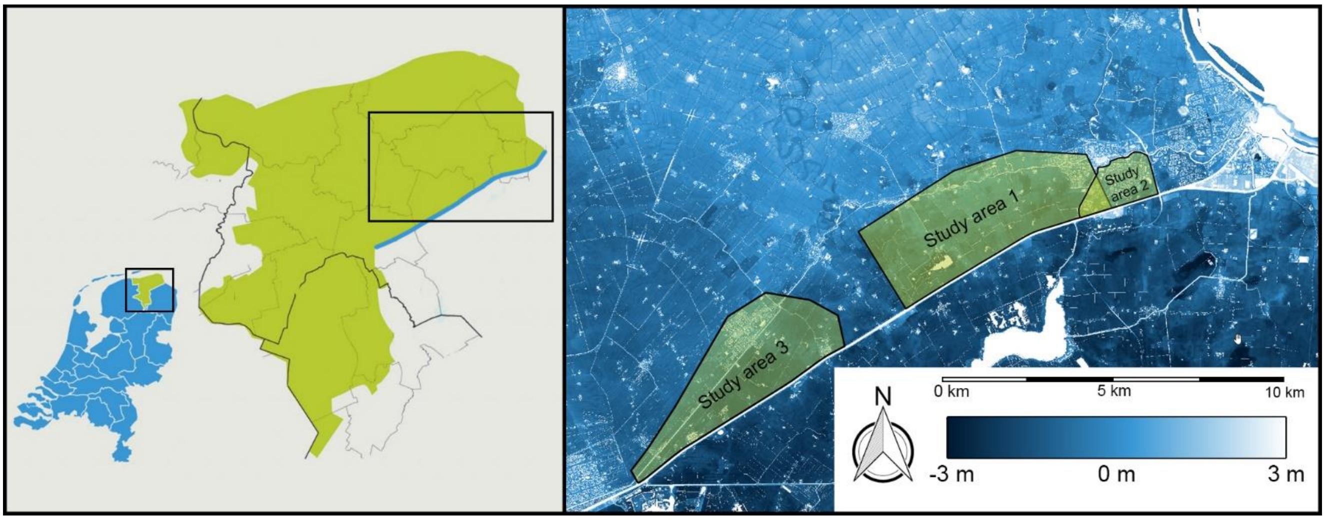


Figure 3: Study area near the Eemskanaal, with the DEM of the area (white represent no data values). On the right, the three study areas that have been used in the sensitivity analysis.

The Eemskanaal connects Groningen to Delfzijl and is important for shipping. The channel is not directly connected to the sea, since there are sluices at Delfzijl that separate the channel from the sea water. The Eemskanaal has a width of 60 meters, and a length of 26.5 km. For the simulations, the Eemskanaal is treated as a finite volume channel, with no inflow from any other sources. All the water that flows through the dike breach, is subtracted from the total volume of the channel.

North of the Eemskanaal there mostly is a rural area, with small villages. At the west, there is the city of Groningen, however the city has a higher elevation level, and has not been inundated in the performed simulations. At the connection with the North Sea, Delfzijl is located. This area has been inundated with dike breaches near Delfzijl. Delfzijl has about 46 thousand inhabitants.

For the comparison to TYGRON, 3 different study areas across the management region of the waterboard are chosen. These areas have been chosen since the TYGRON results of these areas where the most accurately reproducible. This allows for an accurate comparison. The selected areas can be seen in Figure 4. Both comparison locations 2 and 3 involve a dike breach at the North Sea, for these dike breaches, a steady water level in the North Sea is assumed, since this was also done in the TYGRON simulation. Dike breach location 1 is at the Eemskanaal, and for this a finite volume channel is assumed, with a reducing water level as water flows through the dike breach.

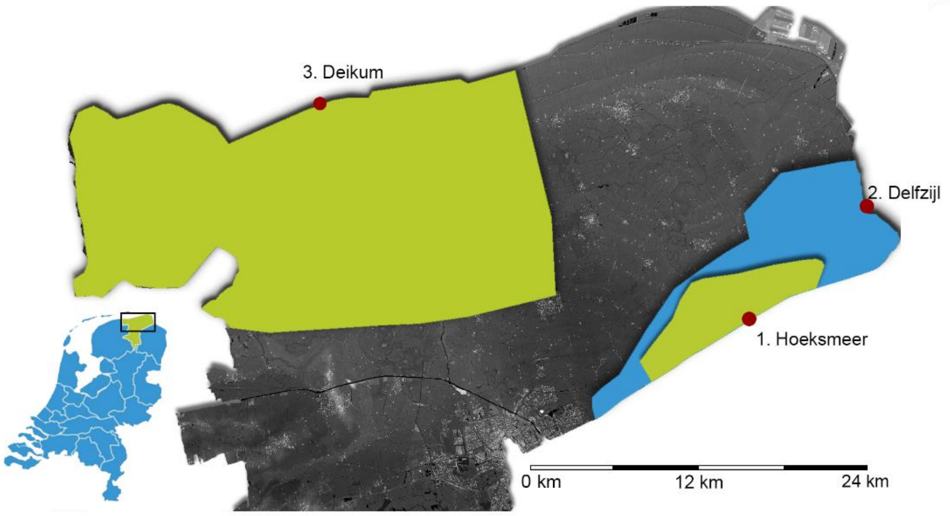


Figure 4: All three study areas for the comparison between D-HYDRO and TYGRON.

4.3. Hardware

For this study, the waterboard has provided a laptop. The laptop used for performing all simulations is: HP ProBook 450 G6. The hardware specifications for this laptop can be seen in Table 2.

Table 2: Hardware specifications

Processor	Intel Core i5-8265U CPU @ 1.60 GHz 1.80Hz
RAM	8 GB DDR4 RAM (7.87 GB available)
Ram speed	2400 MHz
Type	64 bit, x64 processor

4.4. Model output

To make comparisons between the results of different models, it has to be established what output is compared to each other. Speaking to people from the waterboard, there are multiple important decisions that can be made based on the output of a flood model. Examples of such decisions are the evacuation of cattle (to prevent economic/social damage), evacuation of people (to prevent social damage) and laying sandbags to create temporary dikes (to prevent economic and environmental damage).

Direct economic damage can be calculated from flood depth and land use (Jonkman et al., 2008). To estimate indirect economic damage, a model is needed that is able to assess the impact of a flooding on business related activities (Jonkman et al., 2008). The potential loss of life can be estimated with the flood characteristics, the number of people exposed, and the mortality rate (Jonkman, 2007). Flood characteristics are the water depth, flow velocity, rise rate, time of arrival, and available preparation time.

Water depth and flow velocity over time are both easy to extract from the D-HYDRO model. Maximum water depth and flow velocity over the course of the entire simulation are currently not easy to export since the gathering of this data cannot be initiated from the GUI in the current beta release. Therefore, for this research, the water depth and flow velocity at certain time steps are used.

The water depth is the main output used in comparing model outputs, since the water depth in the modelled area gives a good insight on the flood propagation of a model. The flow velocity is not always reported, except if the results are noteworthy. This is because the flow velocity is very time and location dependent, flow velocities can fluctuate significantly at different time steps. Therefore, it is difficult to show within single images. The water depth is more consistent over time, and therefore considered a better indicator for this comparison.

4.5. Sensitivity analysis

For the sensitivity analysis, 2 main study areas are considered (study area 1 and 2). Study area 1 has a bigger surface area and is a more rural region. Study area 2 is smaller, and more urban. Study area 3 is used for a specific case since this area contains the waste water treatment plant of Gamerwolde, which is an essential structure for all inhabitants in the area. The study areas can be seen in Figure 3.

When conducting the sensitivity analysis, it is important that only a certain variable is modified to test the effect of this variable. For this reason, when conducting the sensitivity analysis on the D-HYDRO model itself, a fixed water inflow from the dike breach is used, that does not change over time. This is done because different models can be compared more accurately to each other. It is not the most accurate representation of a real-life dike breach; however, it does provide equal circumstances over multiple simulations.

Throughout most of the performed tests for the sensitivity analysis, the discharge through the dike breach is $25m^3/s$ and a 24 hour period is simulated. If in a test the discharge is different, this is mentioned. A discharge of $25m^3/s$ represents a dike breach in the Eemskanaal of about 10 meters. The only data input for the base model used in the sensitivity analysis is a DEM of the area. This DEM is interpolated over a grid of varying size. Additional data inputs are tested in the second part of the sensitivity analysis.

5. Results

5.1. Sensitivity analysis on model set up

This sensitivity analysis is focusses on the basic components of a 2D hydraulic model. These components are the grid size, the DEM, and the Courant number.

5.1.1. Grid size and DEM

Grid size is expected to have a significant impact on both computation time and model accuracy (Falter, et al., 2012). With a coarser grid, details in the environment are averaged out. Furthermore, larger grid cells means fewer grid cells to represent an area, which means less calculation have to be performed.

The DEM used is the AHN3 height map of the Netherlands. This is a map with digital elevation data for the Netherlands. This map is made using a technique called LIDAR. DEM maps made with this technique are proven to be a good input for flood modelling (Papaioannou et al., 2015). The AHN3 map that is used does not contain elevation data for buildings and water bodies. This causes "no data" values to be present in the DEM. Different ways have been tested out to fill those no data values. In short:

Method 1: No data values are filled based on elevation data in neighbouring area. For example: a small ditch in a meadow has no data in the AHN3 dataset. Then for these no data values, the same elevation is assigned as the meadow next to the ditch. (about 5 minutes to create)
Method 2: Method 1, but all waterways are excavated to be 1.5-meters deep. All buildings are made 8 meters tall (about 50 minutes to create). For more details, see Appendix D: DEM excavation.
Method 3: Similar to method 2, but waterway depth is determined by their geometry, broader water ways are made deeper (about 80 minutes to create). For more details, see Appendix D: DEM excavation.

It should be noted that this is just the DEM, not the actual model. The DEM might contain a 0.5 meter wide ditch, however in a model with grid of 20 meter, this would not be noticeable.

As a reference for how much the DEM is changed: within the rural study area 1, there are 2961 buildings within the area, and 807 waterways. For the urban study area 2, there are 4037 buildings and 165 waterways. More details about the methods can be found in Appendix D: DEM excavation.

For this test, grid sizes of 20*20, 10*10 and 5*5 meters have been tested. These grid sizes are chosen since they have manageable computation time on the available hardware. Table 3 shows the results of the models to test grid size. As expected, there is a clear relationship between grid size and computation time. Figure 5 shows a comparison between all the different grid sizes that have been tested for study area 1.

Table 3: Results for simulations to compare grid resolution and different DEM's for study area 1.

Grid size	Estimated grid cells in area	Average computation time (hh:mm:ss)	DEM excavation method	Inundated area (km^2)	Average inundated area (km^2)
100*100	1800	00:00:05	3	3.94	3.94
50*50	7200	00:00:16	3	3.90	3.90
20*20	45000	00:02:43	1	3.82	3.77
			2	3.84	
			3	3.64	
10*10	180000	00:32:40	1	3.90	3.99
			2	4.14	
			3	3.94	
5*5	720000	03:49:24	1	4.07	4.28
			2	4.21	
			3	4.55	

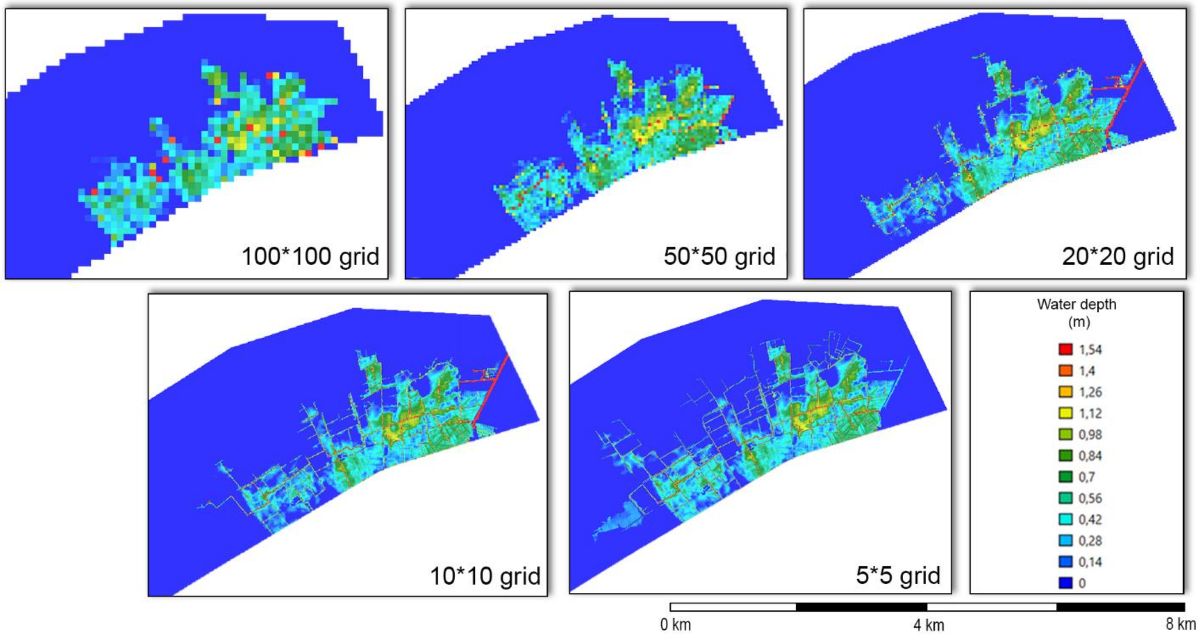


Figure 5: Results after 24 hours for study area 1 with all different grid sizes, with DEM excavation method 3.

More images of the results can be found in Appendix C: Grid size and DEM. The clearest difference between the grid size versions is that in the 5*5 models, waterways are represented more accurately. With larger grid cells, the small waterways get lost since there is not enough detail in the grid. With smaller grid cells, the waterways are represented better, and the water can travel through them. However, this does not have a big impact on the overall region that is flooded, this region is quite similar for all the models. It should be noted that this also depends on the area. If the area would contain a 10 meter wide dam, the smaller grid size models would see an effect of this dam, however with the largest grid cells it would get averaged out completely. This could lead to big differences in the inundated area.

From Appendix C: Grid size and DEM, it is concluded that DEM excavation method 2 and 3 perform quite similar, excavation method 3 resulted in slightly more waterways containing water. It is hard to say if this is more realistic since there is no historical data to compare to. However, using basic reasoning, it is more realistic to assign different depth values based on the geometry of the waterway. The method used here is not a perfect representation of the real world, but it is a good estimation with the data that is available.

Comparing methods 2 and 3 to method 1, there are some differences. These differences are mainly in water ways. However, the overall flooded area is quite similar as can be seen in Table 3. Also, the water depths within the flooded areas are similar, as can be seen in Figure 42.

From Table 3 it can be seen that with more detailed grid cells smaller than 20 meters, the inundated area increases as the grid cell size decreases. This is because with more detailed grid cells, waterways have more of an effect allowing for the water to spread over the area. With grid cells larger than 20 meters, this effect is not present, at these grid sizes, the total inundated area increases due to the large grid cells. Small obstructions lose their detail, allowing for different spread of the water. A visualisation of the total inundated areas for different grid sizes of 20, 10 and 5 meter can be seen in Figure 6.

Figure 6: Inundated area for study area 1 with a 20 meter grid (red), 10 meter grid (blue), and 5 meter grid (black)

A similar grid size test has been performed on study area 2. This is to test the effect of a more urban region on the grid size. Also, since the area is smaller, smaller grid sizes can be tested. The DEM is constructed according to method 3. This is done since from the previous tests, method 3 is deemed to be the most accurate way of using the DEM information for flood simulations. In Table 4 the results of this test can be seen. Figure 7 shows the result of the 10*10 and 2*2 model. More images of the results can be found in Appendix C: Grid size and DEM.

Table 4: Results after 12 hours for study area 2.

Grid size	Estimated grid cells in area	Computation time	Inundated area (km^2)
10*10	30000	00:11:24	1.69
5*5	121000	02:23:00	1.73
2*2	758000	33 hours*	1.73

*Computer went to sleep during simulation, exact running time not available, between 32 and 34 hours.

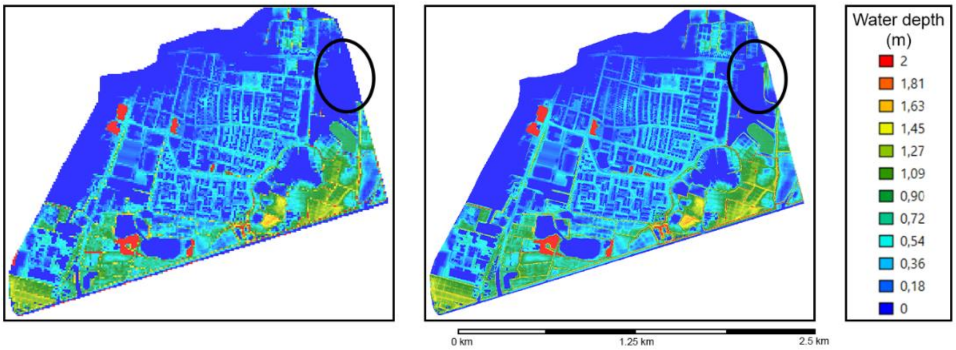


Figure 7: Comparison of 10*10 grid (left) and 2*2 grid (right), black circle highlights a difference in the inundated land area. Both models simulate a 12 hour period after the dike breach for study area 2.

Like in the previous tests, the higher resolution gives a better view of the details within the modelled area. However, these details have little effect on the overall area that is flooded. The 10*10 model misses one area that is flooded in the 2*2 model, highlighted with a circle. This is part of a motorway exit, so the area could be critical. Apart from that, there are only differences in the details. 2*2 has a very long computation time. For this reason, it is decided to not use models with 2*2 meter grid size or smaller anymore.

DEM accuracy relative to grid size

Within the tests in this chapter, a 5*5 meter DEM has been used. In Appendix E: DEM accuracy relative to grid size, it is tested what the effect of having a more detailed DEM is. Within the test, the effect of using a 5*5 vs a 2*2 DEM is tested. Overall, the differences are minor, but in general it is better to use a more detailed DEM if it does not influence the set up time significantly. The tests and their results can be found in Appendix D: DEM excavation.

5.1.2. Flexible mesh

As shown by the tests in chapter 5.1.1, the grid size does have a big impact on model computation time and a moderate impact on model accuracy. D-HYDRO offers the possibility to have multiple different grid cell sizes, within one mesh. The advantage of this is that a detailed grid can be used for areas where this is required. And a coarse grid can be used for areas where no detail is required. This saves computation time, while maintaining detail in areas where this is required.

There are multiple methods to refine the grid. The refinement locations can be set with polygons imported by the users, or they can be based on a raster input. For the tests, refinement based on a polygon input has been used.

To make a refined grid, first a coarse grid is constructed (20*20). Then, an area is selected. This area can then be refined. By refining one time, the grid size in the selected area becomes 10*10 meters. A second refinement results in a grid size of 5*5 meters. For the refinement tests that are done, the main water ways have been refined. In Figure 8 the refinement locations can be seen.

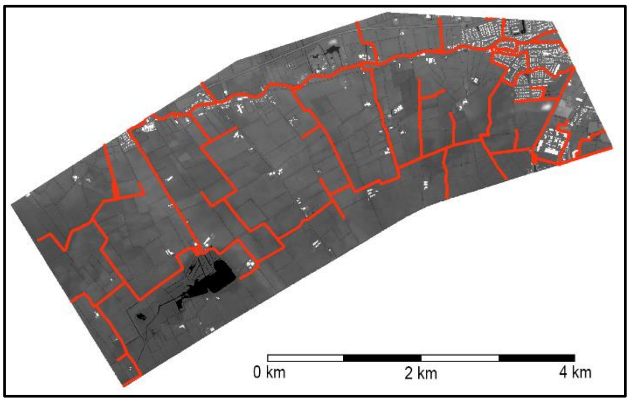


Figure 8: Refinement locations marked in red for Flexible mesh in study area 1.

In Figure 9, the results of different flexible mesh set ups can be seen. The figure shows results after 24 hours, at earlier time steps, similar patterns in the results occur. Water has a wider spread because it can travel through waterways when the grid size is smaller. This spread through waterways is not present at the 20*20 model without refinements, since waterways were averaged out because of the large grid size.

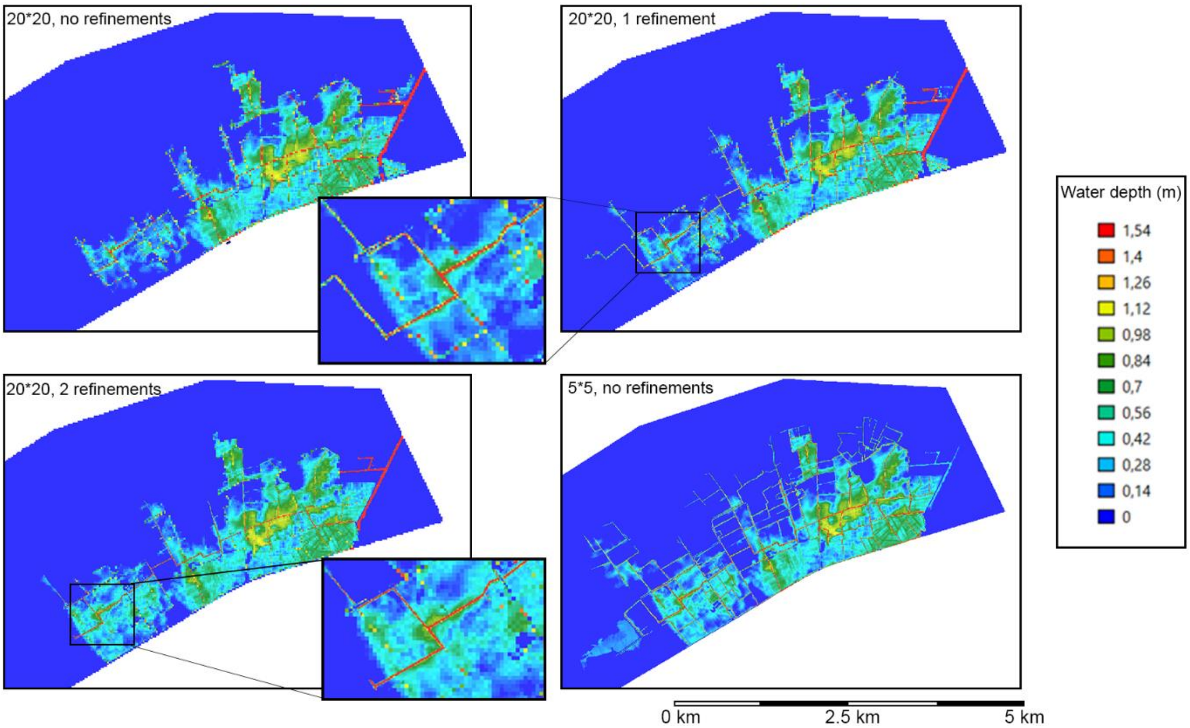


Figure 9: Flexible mesh results after 24 hours for study area 1. 20*20 no refinements (top left), 20*20 1 refinement (top right), 20*20 2 refinements (bottom left), and 5*5 no refinements for comparison (bottom right)

Table 5: Computation time and total inundated area for flexible mesh models of study area 1, all models simulate a 24 hour period after the dike breach.

Base resolution	Refinements	Run time (hh:mm:ss)	Inundated area (km^2)
20*20	-	00:03:10	3.47
20*20	1 refinement, 40 meters around main water ways. So, 10*10 at refined locations	00:14:00	3.64
20*20	2 refinements, 50 meters around main water ways. So, 5*5 at refined locations	00:43:15	3.72
5*5	-	04:11:00	4.33

As expected, additional grid refinements cause longer computation times. Looking at the figures, the output has changed by increasing the refinements. Like in previous tests, the overall inundated area is similar. But with more refinements, the results do get closer to 5*5 grid, even though the computation time is significantly smaller. The increase in accuracy can mainly be seen visually, and by an increase in the inundated area in Table 5. The increase in accuracy comes with an increase in computation time, however the computation time with a refined grid to 5*5 is still significantly shorter than a full 5*5 resolution.

Small ditches are not visible in any of the 20*20 refined models, which is logical. These were not part of the refined area since they are not part of the main water ways.

Overall, flexible mesh is a promising solution to save on computation time while maintaining accuracy. It preserves the terrain detail in important areas where the water is expected to flow. While saving computation time by having a coarse grid on location where the detail is less important. More tests that validate this conclusion can be read in chapter 5.3.

On the downside, D-HYDRO is currently quite unstable while working with flexible meshes. Saved projects sometimes lose their bed level information and interpolation can cause weird results in the GUI. This can make working with flexible mesh unreliable. Deltares is working to improve this in later releases of D-HYDRO. Another disadvantage of flexible mesh is the required buffer around areas that need to be refined. This buffer has to be made by the user, and it can take some time to get the right buffer. However with some experience, this becomes easier.

5.1.3. Time step (Courant number)

The Courant number determines the computational time step in the model. A higher Courant number leads to longer time step, and therefore a lower computation time. The goal of this test is to find out how the Courant number affects the computation time and accuracy. To do this, multiple versions of the same model have been run, with different Courant numbers.

The Courant number determines the time step based on the velocity of the water and the grid cell size. The goal is, that a water unit can never travel more grid cell distances than the Courant number allows. With higher Courant numbers (>1), water could potentially flow a distance greater than 1 cell within 1 timestep. This causes water to "skip" certain cells. Because D-HYDRO uses an explicit scheme, it is advised to use a Courant number below 0.7. With an explicit scheme, parameters are calculated based on the previous time step. The parameters are not dependent on each other (Moin, 2010).

Figure 10 shows the computation time for different Courant numbers. From the graph it can be seen that the Courant number and the computation time are strongly related.

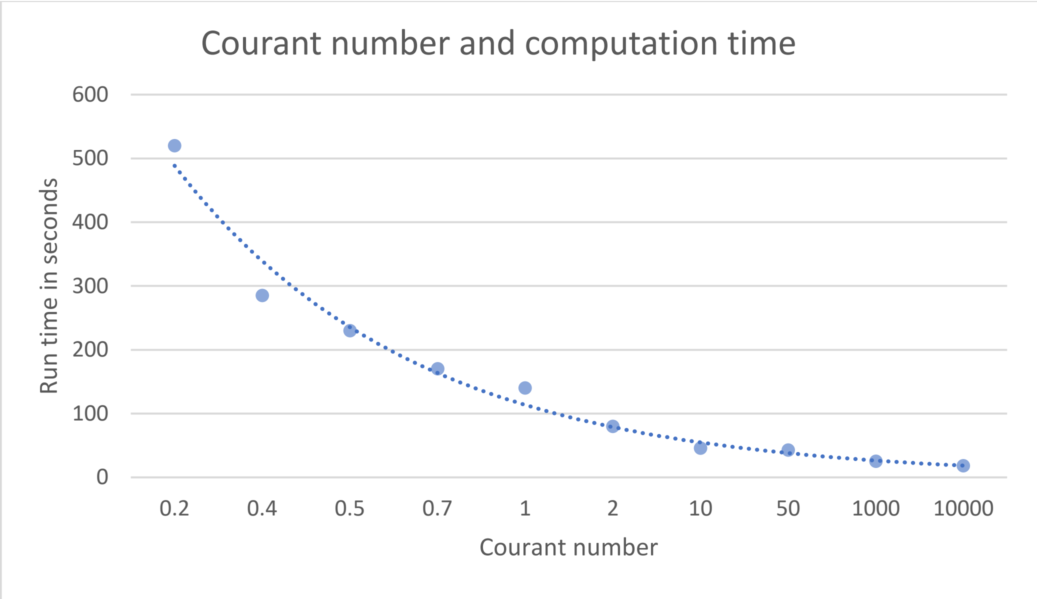


Figure 10: Computation time for different Courant numbers. 20*20 model of study area 1.

Surprisingly, Courant numbers up to 50 have shown accurate results. This was not expected, since Courant numbers above 1 are not advised to use. Therefore some additional research and testing has been done on the Courant number. This research can be read in Appendix G: Courant numbers. From the additional research, the following conclusion has been deducted:

The Courant number of 50 has been usable and did not affect the output, because the Courant number is determined at the highest velocity point in the field. Most of the field however, has a significantly smaller velocity. By increasing the maximum Courant number in the field, most of the cells still have a Courant number <1. Because the velocity at most locations, is significantly lower than at the highest location in the field (see an example in Figure 11). For this reason, the inaccuracy that might be created in cells with Courant number > 1, is negligible compared to the other cells. This of course depends on the Courant number chosen.

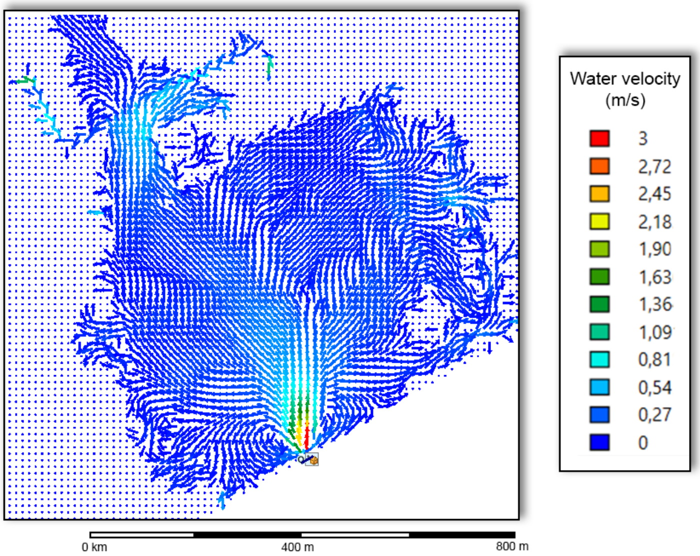


Figure 11: Flow velocity near the dike breach for study area 1. Flow velocities near the breach are significantly higher than velocities in the rest of the inundated area.

Even though many tests have shown accurate results, it is still not advised to use Courant numbers greater than 1. Not enough testing has been done to conclude a higher Courant number always provides more accurate results. However, it is an interesting subject, and additional research can be done on how to use this to get faster computations. Possibly a feature where certain areas can be excluded for the Courant condition.

Grid size on computation time

Overall, grid size has a big impact on computation time. An increase in grid size with factor x, causes the amount of grid cells required to represent the area by a factor of x2. The amount of grid cells required to represent the area directly affects computation. With more grid cells, more calculations need to be performed.

However, the relationship between grid cells and computation time is not linear to the amount of grid cells used. This is for multiple reasons. A big factor is the time step the model uses. With smaller grid cells, the time step that the model can use is smaller. The time step is calculated with the help of the Courant number. This is done according to equation 5 (Deltares, 2020a).

$$C = \max\left(\frac{u_x \Delta t}{\Delta x} + \frac{u_y \Delta t}{\Delta y}\right) \tag{5}$$

Equation 5 determines the maximum Courant number in the field. By increasing the grid size by factor Z, Δx and Δy increase by the same factor Z. Both velocities u_x and u_y stay roughly the same (it is the same model, with only varying grid size, so flow velocities are similar). Therefore, to have the same Courant number, the Δt must be increased by approximately the same factor Z. This is one of the reasons why the relationship is not linear, however there are more factors that add to this.

5.1.4. Discussion sensitivity analysis on model set up

During most tests in this chapter, there was no access to the 0.5m DEM yet (downloads from servers of Noorderzijlvest failed). Only the 5m DEM has been used for this time. The final method (method 4 in Appendix D: DEM excavation) of DEM excavation is based on the 0.5 meter resolution map. More about this method can be read in Appendix D: DEM excavation.

When calculating the total inundated area, the waterways that are inundated also count as inundated area. This is not realistic since there is not flooding when water is in a waterway.

5.2. Sensitivity analysis on model additions

In this sensitivity analysis, it is tested how different additions to the model affect the model output. The tests are all performed on a 5*5 meter resolution model. This is because at this resolution, calculation times are manageable for the equipment used. Not every effect of changes on the model input data are the same on a model with a lower or higher resolution than 5*5, however when it is expected that the changes differ for different grid sizes, it is noted. A fixed grid is used for these tests, since D-HYDRO causes less errors working with fixed grids. Flexible mesh has been tested in chapter 5.1.2, and additional tests on flexible mesh are done in chapter 5.3.

The first model that is used for these tests, is a 5*5 meter model for study area 1. The inflow is 25 m^3/s, and the model is run for 24 hours. The Courant number is set at the default of 0.7. The second model is a 5*5 model of study area 2. This model has an inflow of 15 m^3/s, representing a smaller breach. Study area 2 is a more urban area than study area 1. This model is tested for 12 hours on 0.7 Courant. The only input data for the basic models is the DEM, a dike breach location, and the grid.

The following topics are researched:

-Culverts
-Roughness values
-Precipitation
-Wind
-Dams
-Weirs
-Angular grid
-Model size
-Initial water levels
-Breach inflow

5.2.1. Culverts

A culvert functions as a connection of two waterways. This allows for water to flow between the two waterways. In the DEM from AHN3, culverts are not represented since they are tubes underground. These are not measured with the LIDAR technique. (AHN, 2020) To test the effect of culverts, the DEM has been excavated. This allows waterways to be connected to each other. The excavation depth depends on the culvert size, and generally this is not as deep as the water way itself. More about the DEM modifications can be read in Appendix D: DEM excavation. The locations of the culverts within study area 1 and 2 can be seen in Figure 12.

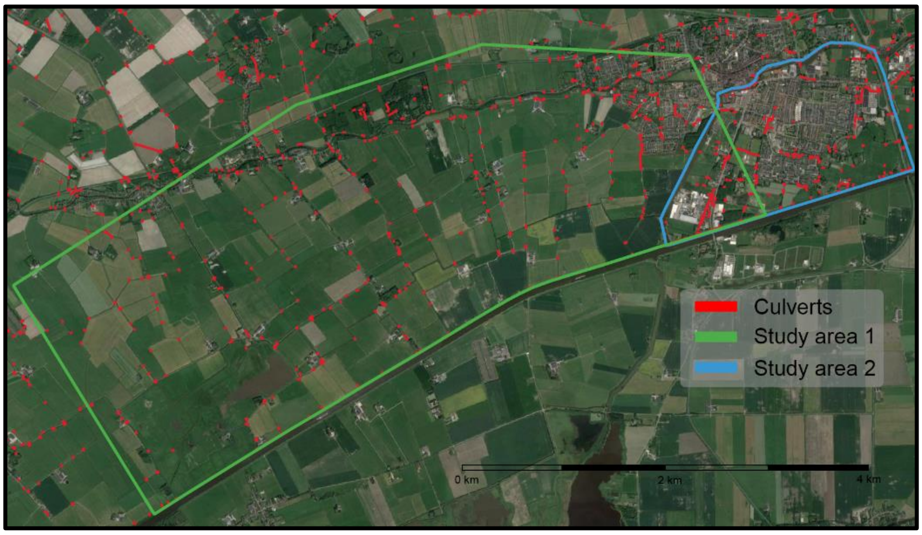


Figure 12: Culvert locations in study area 1 and study area 2. Culverts are scaled up in this image in order to be visible.

With this way of including culverts, culverts are represented as open channels and their tube-like geometry is lost. This causes that the discharge trough culverts can be higher than in real life. This is not expected to change the results, but it should be noted.

The first test contains culverts with their actual size, if the size is smaller than 2-meters, it is enlarged to 2-meters. This ensures that the culverts are represented at the 2m DEM. The second test contains culverts with a size of 6 meters. This is done, to make sure the culverts are represented fully on the 5-meter grid in D-HYDRO. This ensures that water ways connected by a culvert are also connected in the D-HYDRO model. A different possible method that has not been tested is sizing the culverts up the size of the width of the waterways that it is connecting. The results of the test on study area 1 can be seen in Figure 13.

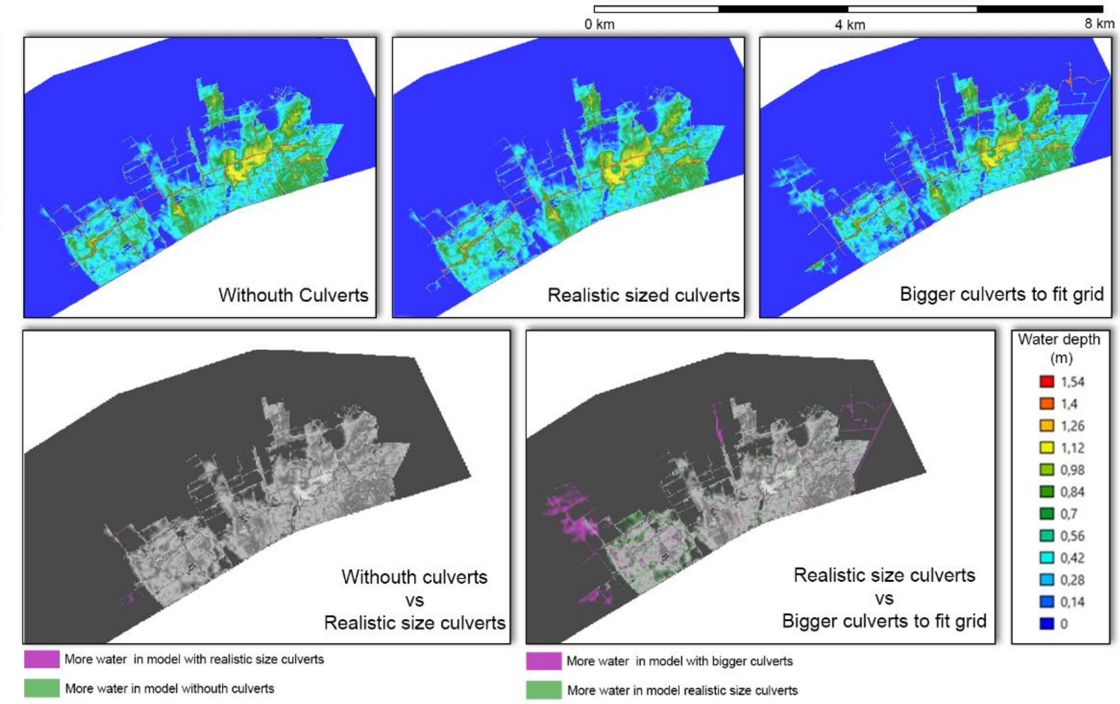


Figure 13: Results for study area 1 without culverts (top left), results with realistic size culverts (top middle), results with bigger, 6 meter wide, culverts(top right), and their comparisons (bottom).

Table 6: The effect of culverts on the inundated area in km^2.

Model	**Inundated area (km^2)**	**Percentual change from base model**
No culverts	4.01	-
Regular culverts	4.02	0.3%
6 meter wide culverts	4.36	8.1%

Comparing the base model to the normal excavated culverts, the results are nearly identical. Some differences have been highlighted in purple/green; however, these differences are very minor. On the other hand, with the bigger culverts of 6 meters, the results did significantly change. Additional areas have been inundated that were not inundated before. This change in inundated area can be seen in Table 6. Also, significant differences can be seen at results after 6 hours (Figure 14). Some waterways that were not inundated with regular culverts, are inundated with the 6 meter wide culverts. This shows, that with the regular culverts, these waterways were not connected yet, since water could not flow through the water way. Culverts allow access to all waterways, by connecting the waterways. This causes water to spread through water channels more realistically, for study area 1, this can especially be seen at the beginning of the flooding.

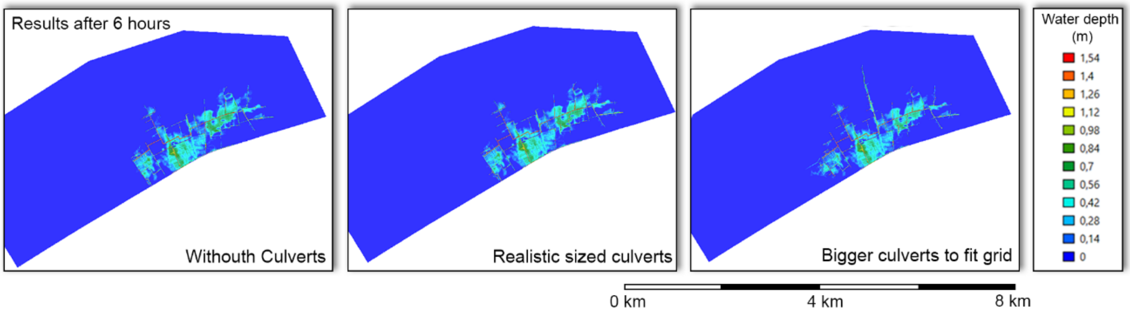


Figure 14: Results after 6 hours for study area 1, here it can especially be seen that with the bigger culverts, more waterways are filled with water.

From Figure 14 it can be clearly seen that with the 6 meter wide culvers, more waterways are filled with water. This implies that in the simulations without culverts, and with regularly sized culverts, the water ways were not connected to each other. The same test has also been performed for study area 2. The results can be seen in Figure 15.

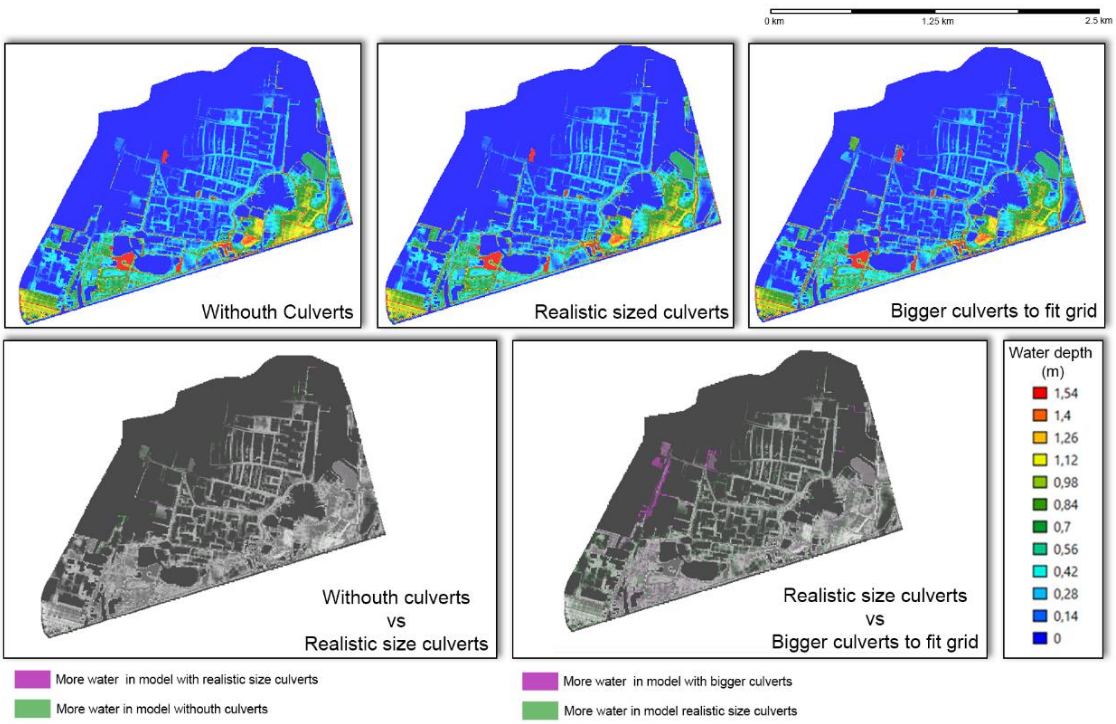


Figure 15: Results for study area 2 without culverts (top left), results with realistic size culverts (top middle), results with bigger, 6 meter wide, culverts(top right), and their comparisons (bottom).

Like in the previous simulation, the effect of normal culverts is hardly noticeable. However, with bigger culverts, some additional areas are inundated, and some other areas are less inundated. The difference in area 2 is less than in area 1 (8% for study area 1 and 4% for study area 2).

Having culverts with a size of 6 meters might seem unrealistic, since this is significantly bigger than most of culverts are in real life. However, this size ensures that waterways are really connected in the model, and that the connection does not get lost when the DEM is interpolated over the 5-meter grid. Culverts are quite small and make up a very small percentage of the total modelled area (0.15% of total area in study area 1 if they are widened to 6 meters). So, increasing their size will barely have an impact on anything else other than connecting water ways.

Table 7: Computation time for 5*5 model with and without culverts

Model (study area 1)	Computation time (hh:mm:ss)	Setup time
No culverts	04:40:15	Regular set up time
Regular culverts	04:39:10	Regular set up time, however modifying the DEM takes additional time since culverts have to be added. But this can be done beforehand.
6 meter wide culverts	04:51:27	

From Table 7 it can be seen that the addition of culverts does not increase computation time. This is logical since essentially nothing changed, apart from small differences in the DEM. It does also not take any extra time to set up the model. It does take additional time to create the DEM. Culvert data has to be imported, modified, and applied to the DEM. Compared to creating the rest of the DEM, this is also minor. And this work can be done before any alarming situations, since data is already available.

Overall, adding culverts to the DEM does give a more accurate presentation of the real world. However, to ensure that the model calculates the function of the culverts well, the size of the culverts must be matched to the grid size of the model. In the tests, the culverts were scaled up to 6 meters, to ensure a good representation on 5-meter grid cells. This changed model output significantly compared to more realistic sized culverts. Depending on the grid size of the model, it is advised to include culverts. With grid sizes >10 meters, it is advised to not scale up the culverts to match the grid size. For a grid size between 1 and 5 meters, it is advised to scale up the culverts to a size corresponding to the grid cell size. With grid size <1 meters it is advised to use the realistic culvert data, since at this scale realistic culvert data matches the grid size.

5.2.2. Roughness values

Roughness values simulate the terrain by changing the bottom friction between the water and the land. The default manning roughness coefficient in D-HYDRO is 0.023 and is constant over the entire area. The addition of roughness values dependent on the land use can enhance the precision of the simulation, with roughness values representing different land use characteristics (Dottori & Todini, 2012). To test how the addition of roughness values can affect the simulation, roughness values depended on the land use have been added. The roughness values vary per location, based on the type of land of the location. The roughness map for both study area 1 and 2 can be seen in Appendix H: Roughness values. The resulting output can be seen in Figure 16 and Figure 17.

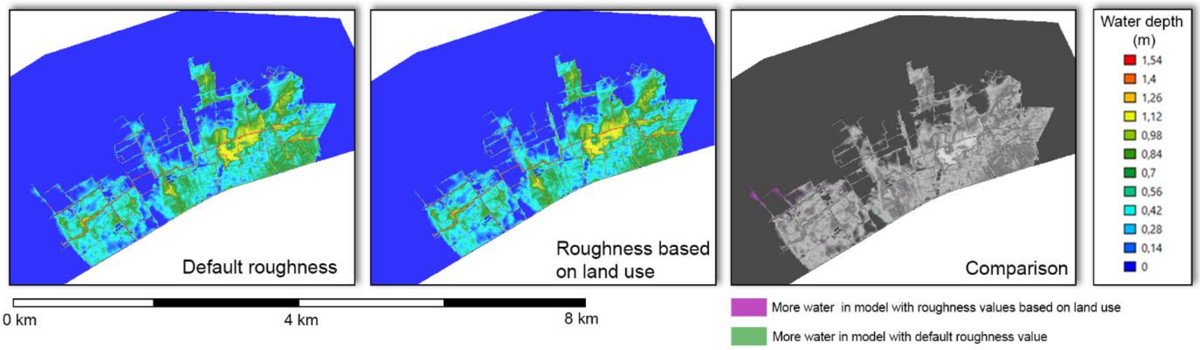


Figure 16: Output for study area 1 after 24 hours of base model with default roughness value of 0.023 (left), model with land use dependent roughness values (middle), and the comparison between the two (right) for study area 1.

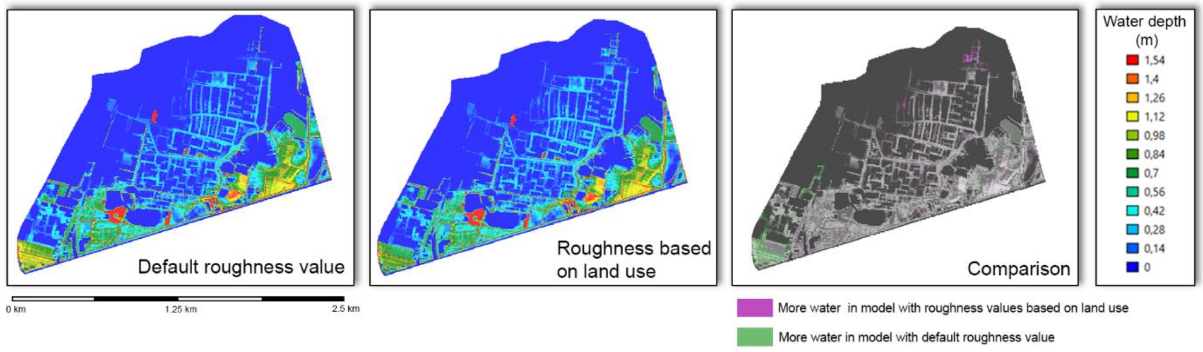


Figure 17: Output for study area 2 after 24 hours of base model with default roughness value of 0.023 (left), model with roughness based on land use (middle), and the comparison between the two (right) for study area 2.

From both the figures it can be seen that the differences are small, in study area 2 there are slightly more differences than study area 1.

D-HYDRO calculates the bed shear stress according to equation 6.

$$\tau_b = \frac{\rho g}{C^2} * u^2 \qquad (6)$$

With τ_b being the bed shear stresses (Pascal), ρ the water density (kg/m^3), g the gravitational acceleration (m/s^2), C the Chezy coefficient (m$^{0.5}$/s), and u the water velocity (m/s).

The Chezy coefficient is calculated from the Manning roughness input according to equation 7.

$$C = \frac{\sqrt[6]{R}}{n} \qquad (7)$$

With n being the Manning roughness, and R being the hydraulic radius. The hydraulic radius is typically equal to water depth H in 2D models (Deltares, 2019b). The relation between bed shear stress and roughness at a water velocity of 0.5 m/s, and a depth of 0.5 meters can be seen in Figure 18.

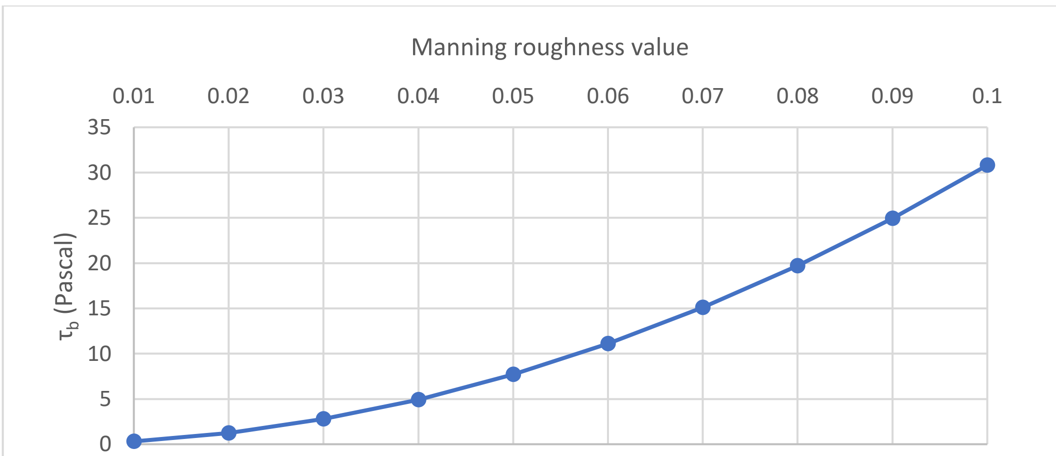


Figure 18: Relation between Manning roughness value and bed shear stress at water level l = 0.5 meter and water velocity = 0.5 m/s.

The default Manning roughness coefficient in D-HYDRO is 0.023. Study area 2 has more variation in roughness values within the inundated area (0.013 to 0.1), whereas study area 1 almost only contains roughness values of 0.035 and 0.4 near the flooding area. From Figure 18 it can be seen that variation in

Manning roughness coefficient can lead to a big difference in the bed shear stress. The difference in shear stress between the default value and the roughness values in study area 1 are small. Whereas in study area 2 there is a larger difference. The forest/park in study area 2 has a Manning roughness coefficient 0.1, generating nearly 30 times as much bed shear stress as the default roughness of 0.023 (Figure 18). To test this hypothesis and to test the importance of roughness values, the Manning roughness coefficient for the entire area is set to 0.1, to simulate a forest like area. This is compared to the default Manning roughness coefficient in D-HYDRO, which is 0.023 for the entire area, to see if a bigger difference occurs.

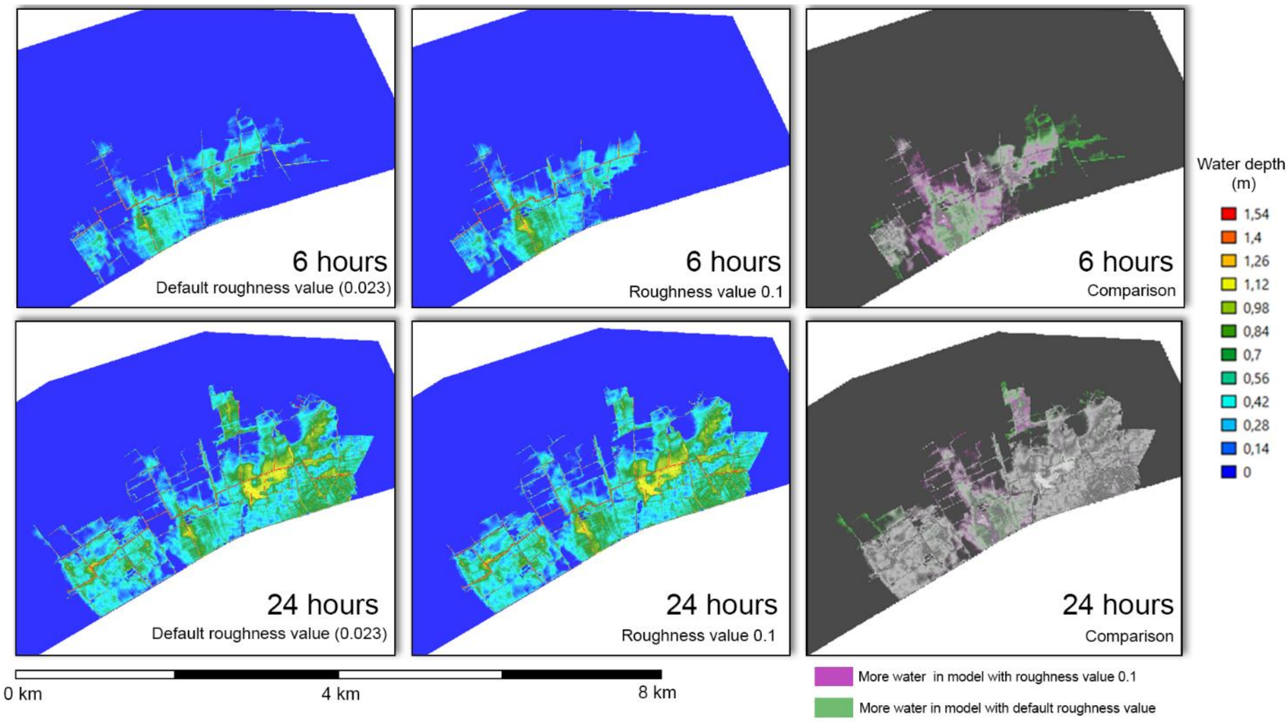


Figure 19: Results for study area 1 with different Manning roughness values of 0.023 (default), and 0.1.

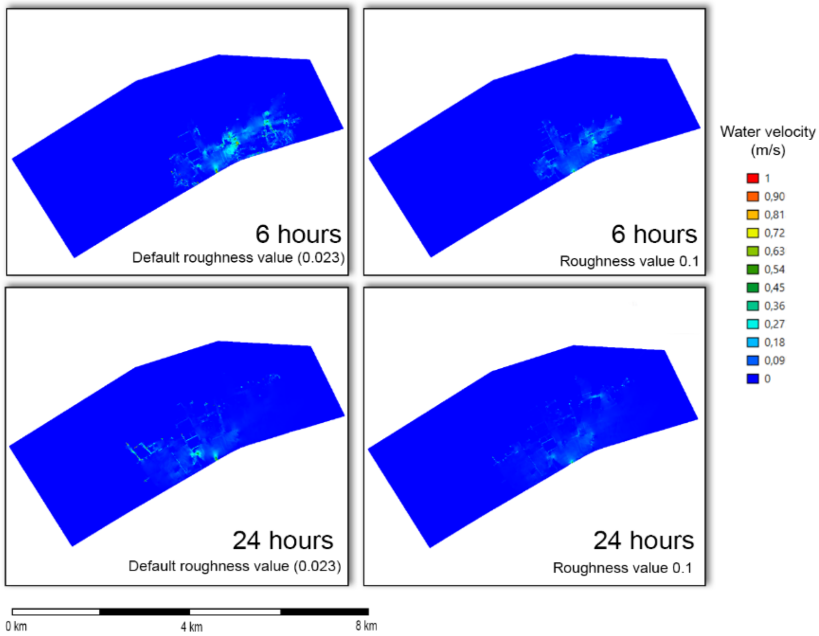


Figure 20: Water velocities (m/s) for study area 1 with different roughness values.

From Figure 14 it can be seen that with a Manning roughness coefficient of 0.1, water spreads less quickly, this is due to increased flow resistance and subsequently lower water velocities. At 24 hours the effect is not so clear, but at 6 hours with a roughness of 0.1, significantly more water is located near the dike breach. In Figure 20, a comparison of the water velocities for the two models can be seen, the model with roughness value of 0.1 has significantly lower water velocities. The lower water velocity also caused the model computation time to be more than halved. This is because with lower water velocities, a longer time step can be used. See Table 8 for the computation times.

Table 8: Computation and set up time for model with and without roughness values.

Model (area 1)	Computation time (hh:mm:ss)	Set up time
Default roughness value over the entire model	04:40:15	Regular set up time
Spatially varying roughness value based on land use	04:36:12	Takes additional time to set up, roughness map must be added and interpolated (2 minutes). Also, a roughness map must be created from the land use map, but this can be done beforehand. This takes about 30 minutes. This map can be made beforehand.
With roughness 0.1	02:06:56	Regular set up time

Adding roughness values based on land use to the model does not require for any additional computations. With the default model, the default roughness value is filled in in every equation, this value simply changed based on location by adding roughness values. Therefore, adding the land use based roughness values did not increase computation time. Actually, with the roughness value of 0.1 it decreased computation time. This is because at this roughness, lower water velocities occur, which allows the model to run with a greater time step. This speeds up calculations significantly. The opposite could also happen, with lower roughness values, velocity could increase and therefore the computation time would increase. However, this is expected to be a less significant effect since the bed shear stress does not change as much for lower roughness values as it does for higher roughness values (Figure 18). To see the result for a different grid size, tests have also been performed on a 20 meter grid, these tests can be found in Appendix H: Roughness values.

It is advised to always use roughness values based on land use for simulations. This is for multiple reasons:

1. Computation time is generally not affected in a negative way by adding roughness values.
2. Easy to set up roughness values, and all the data is available, so that maps with the Manning roughness coefficient for the entire area can be set up beforehand.
3. Detailed environment characteristics are lost with the grid cells in D-HYDRO and by adding roughness values these details are simulated, without significantly increasing computation time.
4. Significant changes in results can be seen for specific situations, especially for land uses with higher Manning roughness values.

5.2.3. Precipitation

To test the influence of precipitation on the model, a constant precipitation rate of 15 mm/day has been simulated. For each grid cell, a certain volume of water per time unit is added. This volume depends on the input precipitation, which is 15 mm/day for this first simulation. This happens at a constant rate throughout the day. 15 mm of rain on a wet day has been determined based on data from the KNMI. (KNMI, 2020a)

Before looking at the results it should be noted that initial water level has not been included in this model (due to malfunctioning in beta version of D-HYDRO that was used). The rain that falls in the area mainly flows to waterways, which is logical. In the base model, all waterways are empty, because there is no initial water level. When precipitation is added, the waterways fill up slightly. The results can be seen in Figure 21.

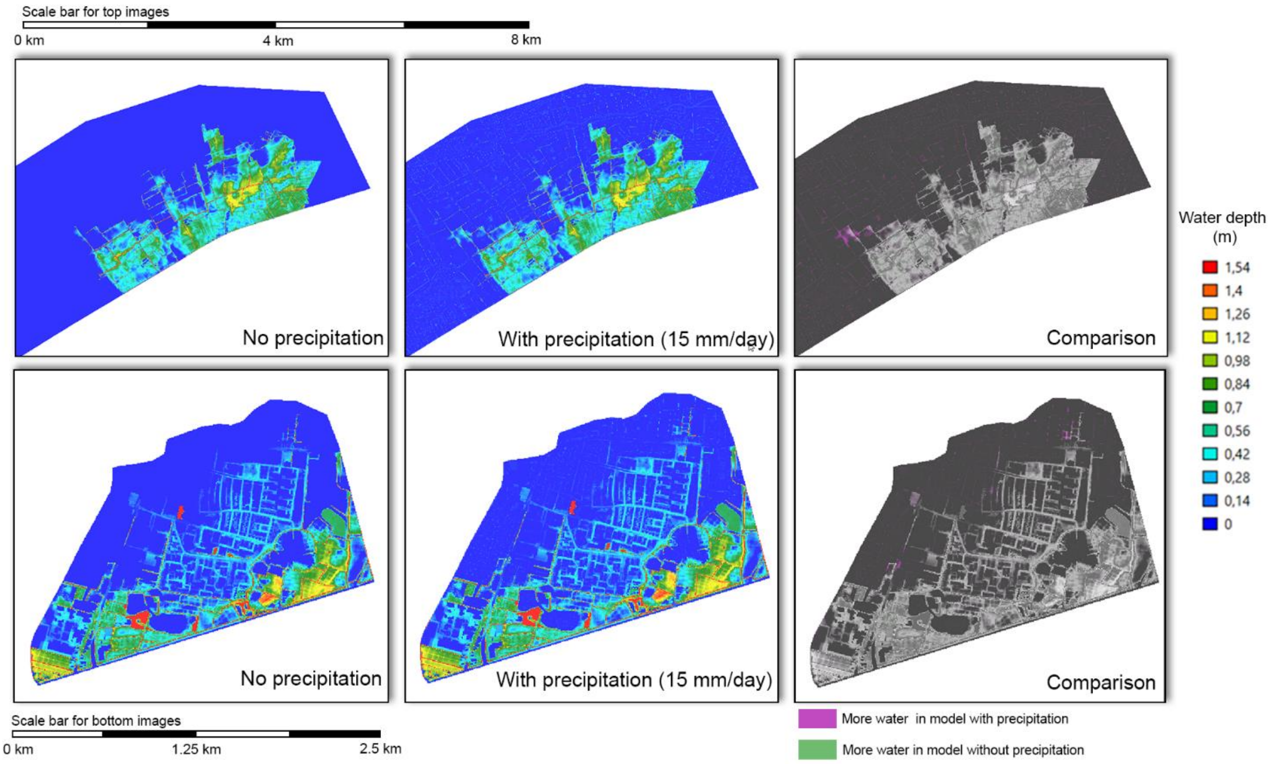
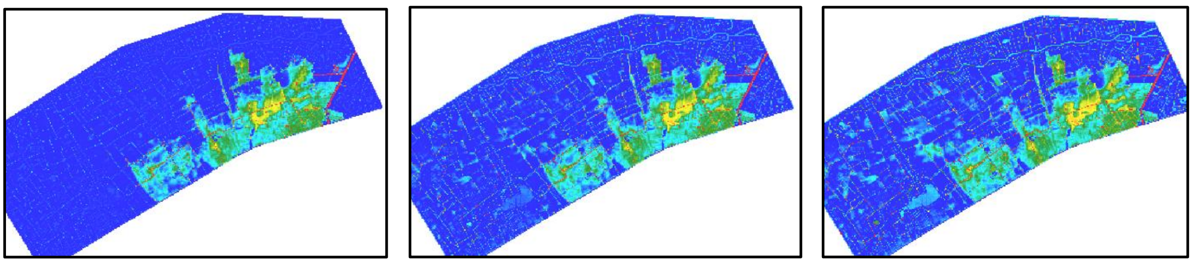


Figure 21: Top: Study area 1. Bottom: Study area 2. Without precipitation (left), with 15 mm of precipitation (middle), and the comparison (right).

Apart from the filled waterways, the differences are minor. For study area 1, there is one area that has been inundated by adding precipitation, highlighted in purple. However overall, the differences are minor. The difference does depend on the precipitation that is added. More precipitation leads to more differences. Additional tests with other precipitation values have been done. These simulations are done on a 20-meter grid resolution. This results can be seen in Appendix J: Precipitation. In Figure 22, some of the results can be seen.



15 mm/day | 60 mm/day | 100 mm/day

Figure 22: Result for study area 1 for different precipitation values (see Appendix J: Precipitation for results for different precipitation values. 15, 25, 35, 45, 60, 80 and 100 mm/day are tested).

From the results in Appendix J: Precipitation, it is clear that with higher precipitation, the flooded area increases. For larger precipitation, floods start to occur outside the earlier inundated region. These floods are just caused by the rainfall, and not by the dike breach. Overall, the increase in the already inundated area is small, even at 100 mm per day. This is because the total amount of additional water due to precipitation of the inundated area is small compared to the breach inflow. This can be seen in Table 9. The results of the additional tests also showed that at precipitation values > 45 mm per day, floods in other regions of the model started to occur, these floods are not related to the dike breach. Because the additional amount of water is a small portion of the breach inflow water, the effects are not so noticeable. Off course, this relation changes by changing the breach inflow, or the amount of precipitation.

Table 9: Relation between the amount of water from precipitation and the amount of water from the breach inflow.

Precipitation (mm per day)	Precipitation on flooded area (m^3)	Percentage of dike breach inflow (%)
15	60000	2.8%
25	100000	4.6%
35	140000	6.5%
45	180000	8.3%
60	240000	11.1%
80	320000	14.8%
100	400000	18.5%

Table 10: Computation and set up time for model with and without precipitation.

Model (area 1)	Computation time (hh:mm:ss)	Set up time
Without precipitation	04:40:15	Regular set up time
With precipitation	10:17:00	Takes additional time to set up, precipitation must be added, the time this takes depends on type of input data. Also, the precipitation data must be gathered and prepared. Together can take from 2 minutes to 1 hour depending on input data (estimation).

From Table 10 it can be seen that computation time has increased significantly: 04:40:15 for the base model, and 10:17:00 for the precipitation model. The reason for this increase is that there are more wet cells in the model. Wet cells require more calculations than dry cells (Deltares, 2019b), and thus computation time increases.

Because of the significantly increased computation time, it is not advised to add precipitation data, except if the precipitation is expected to have a big influence on the results. However, this is only the case if the amount of precipitation is significant in relation to the dike breach inflow.

5.2.4. Wind

D-HYDRO offers the possibility to add the physical effect of wind to the simulation. Wind can cause water to move differently. This is especially true for study area 1 since the area is very flat and has little obstruction for the wind.

To test the effect of wind, a south east wind with speeds of 10 and 20 m/s have been added to the model. This wind is constant during the entire 24 hour simulation. A wind speed of 20m/s corresponds to an 8 on the scale of Beaufort. This is a stormy wind according to the KNMI (KNMI, 2020b). It should be noted that a constant 20 m/s wind for 24 hours is rather extreme, however this is for testing purposes. The results can be seen in Figure 23.

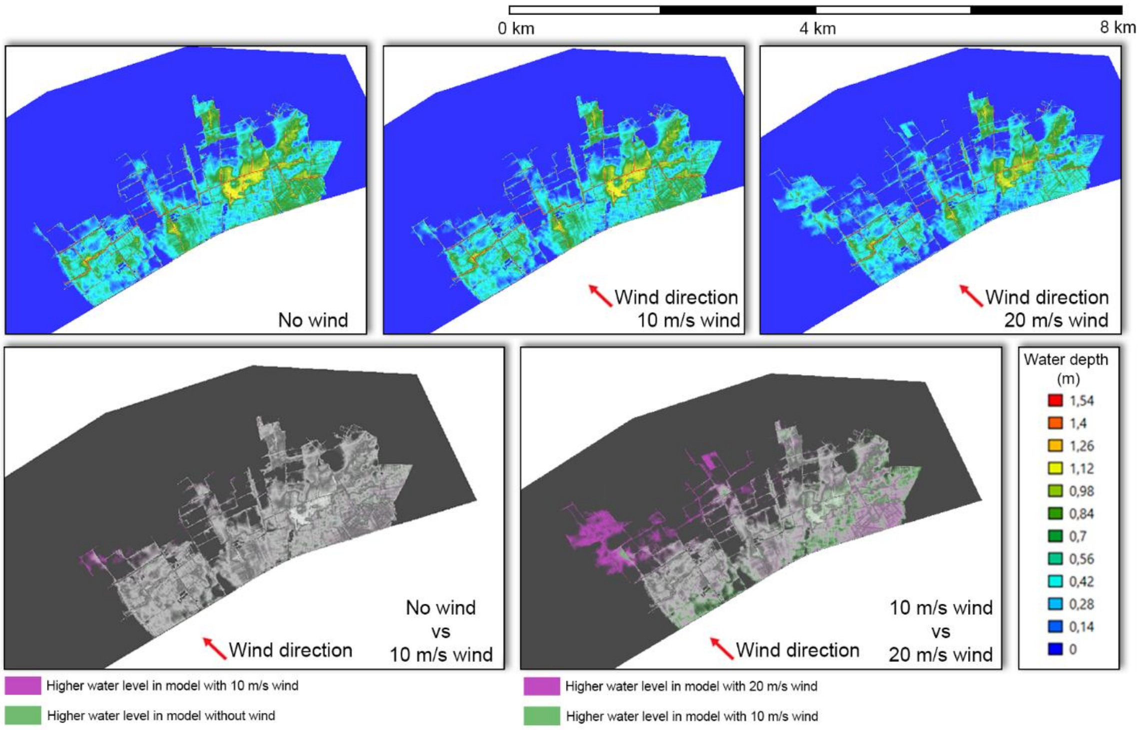


Figure 23: Results for study area 1 without wind (top left), with 10 m/s wind (top middle), with 20 m/s wind (top right), and their comparisons (bottom) for study area 1.

From both Table 11 and Figure 23 it can be seen that the wind has a significant impact on the flooded area. Water has moved along the wind direction, resulting in more flooded area in the North West region. Less water is located at the East and south. Computation time has increased slightly by adding wind data, but this is a marginal increase (04:40:15 vs 04:52:16 for study area 1). The set-up time is almost the same, except that wind data must be added. If this data is available, this can be done within a minute.

Table 11: The effect of adding wind on inundated area for models on both study area 1 and 2.

Study area	Model	Inundated area (km^2)	Percentual change from base model (%)
1	No wind	4.01	-
1	10 m/s wind	4.07	1.5%
1	20 m/s wind	4.86	17.4%
2	No wind	1.22	-
2	10 m/s wind	1.24	1.5%
2	20 m/s wind	1.31	6.6%

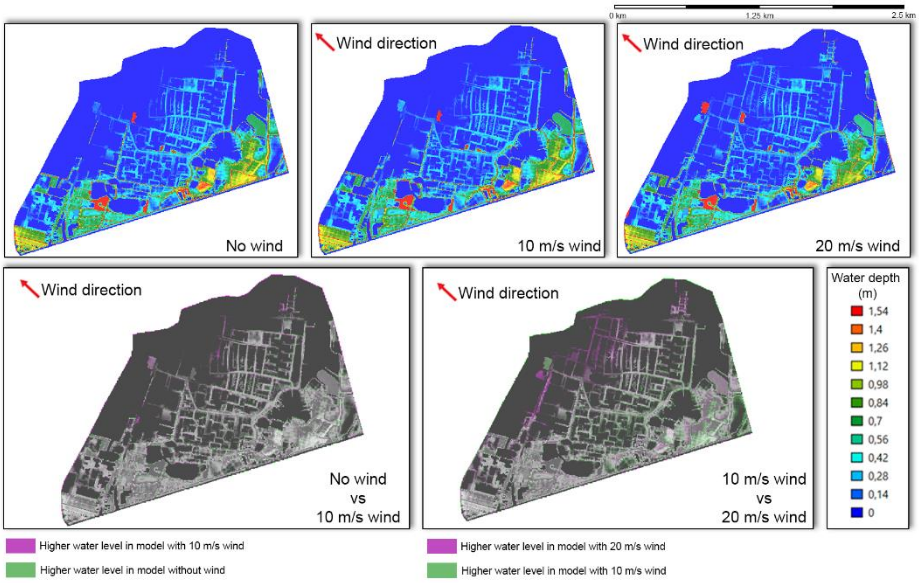


Figure 24: Results for study area 2 without wind (top left), with 10 m/s wind (top middle), with 20 m/s wind (top right), and their comparisons (bottom) for study area 2.

The effects of adding wind on study area 2 can be seen in Figure 24. The wind has had less of an impact on study area 2 than it had on study area 1 (17.4% for study area 1 and 6.6% increase for study area 2). The wind speed for both simulations is the same, and the additional buildings in study area 2 do not affect the wind data. But still study area 1 is more rural, with less changes in height. Therefore, wind can have a bigger impact on this area than on study area 2.

Both the figures, and Table 11 show that the difference between 10 m/s wind and 20 m/s is significant. Where 10 m/s only has a marginal effect on the flooded area of 1.5%, a wind speed of 20 m/s has an effect of 12% on flooded area. Equation 8 shows the formula for stresses due to wind in D-HYDRO.

$$\tau_w = C_d * \rho_a * u^2 \tag{8}$$

With τ_w being the wind stress (Pascal), ρ_a being the air density (kg/m^3), C_d being the air-water friction coefficient (dimensionless), and u the wind velocity (m/s). From the equation, we can see that the wind velocity is squared, which causes quadratically increasing stresses from wind with increasing wind velocity.

For models with a larger or smaller grid size, a similar effect is expected. Also, for models with a different area a similar effect is expected. However, this depends on multiple factors, the most important being the topography of the area. On a meadow, the wind can have a significant impact since meadows are generally flat. However, in an area with more hills, the wind has less of an impact on the inundated area. Also, obstructions in an area like buildings or hills can reduce the wind. However, this effect is not simulated in D-HYDRO, and thus should be accounted for in the input wind data.

To test how different wind speeds affect the simulation, additional tests have been done, these can be found in Appendix I: Wind. These tests are done with a grid size of 20-meter, to save computation time. Different wind speeds (10 and 20 m/s) and 4 different wind directions have been tested. At both 10 and 20 m/s wind speeds, the results were affected by the wind. However, at 10 m/s the effect on the result was substantially smaller than at 20 m/s. The wind direction also had a major effect on the output since it determines where the water is transported.

Table 12: Computation and set up time for models with wind data.

Model (area 1)	Computation time (hh:mm:ss)	Set up time
No wind	04:40:15	Regular set up time
10 m/s wind	04:30:51	Takes additional time to set up, wind must be added, the time this takes depends on type of input data. Also, the wind data must be gathered and prepared. Together can take from 5 minutes to 1 hour depending on the data.
20 m/s wind	04:52:16	

It is advised to use wind data in case it is available. However, with lower wind speeds below 10 m/s, the wind data could be left out since the effect is expected to be small.

5.2.5. Dams

A dam that protects an area against flooding is included in the DEM. Therefore, with sufficiently small grid cell size, these dams do not have to be added manually. However, in many cases, the computation time does not allow for such small grid sizes, and thus larger grid cells must be used. With grid cells larger than the dam, the maximum height of the dam and surrounding area is averaged out over the entire grid cell, resulting in a lower dam. This is not an accurate representation of the real world. In this case, dams must be added manually. It is advised to use the "fixed weir" option for this. In the beta release of D-HYDRO used for this project, it is not possible to automatically import the crest height, therefore, this has been added manually.

To test this, a simulation at the north of the study area has been done. The model simulates a dike breach at the North Sea, both with and without dams manually added. The grid size is 50 meters. This is significantly larger than the dam widths. The results of the test can be seen in Figure 25. This is a simulation for the area that is compared to the TYGRON simulation in chapter 5.3. In this test, a 50 meter dike breach at the sea has been simulated, with a constant discharge of 278 m^3/s. The simulation period is 4 days, the breach is closed after 3 days.

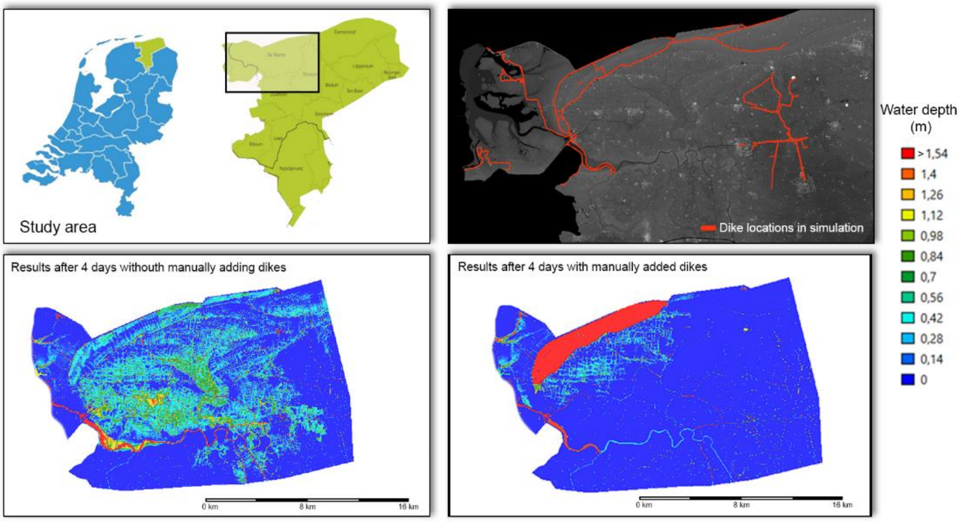


Figure 25: Results before and after adding dikes to the simulation manually in D-HYDRO.

From the results it is clear that adding dikes manually to the simulation has a massive impact on the flooded area. Without adding dike manually, the water spread over the entire simulation area. With manually added dikes, water is caught within the area between the dikes. Water levels within this area are greater than 4 meters at most locations. Only after overtopping the 5 meter high dikes, the water can spread to the rest of the area. This results in a significantly smaller flooded area, as can be clearly seen in Figure 25.

Temporary dam

In case of a flooding, it could be that a temporary dam is created, to protect a valuable area. This dam would not be represented in the DEM, since at the time of recording the DEM the dam is not present. In D-HYDRO, it is advised to use a “fixed weir” and use the crest level as the height for the dam. There also is a thin dam feature, but this feature assumes infinite height for the dam, which is not always realistic.

A fictional scenario for study area 3 has been modelled to test how a dam could affect the simulation. A dike breach near the wastewater treatment plan (WWTP) in Gamerwolde. In the first simulation, a regular flood is simulated. In the second scenario, the army has created a dam to protect the area near the sewage water centre. The sewage water centre is protected since it is critical for the safety of inhabitants of the area. Also, for people outside the flood risk region.

The test scenario model has a resolution of 10-meters. 10-meters is chosen instead of 5 meters because of computation time (1,5 hours vs approximately 12 hours). And the grid resolution is not as important for this test.

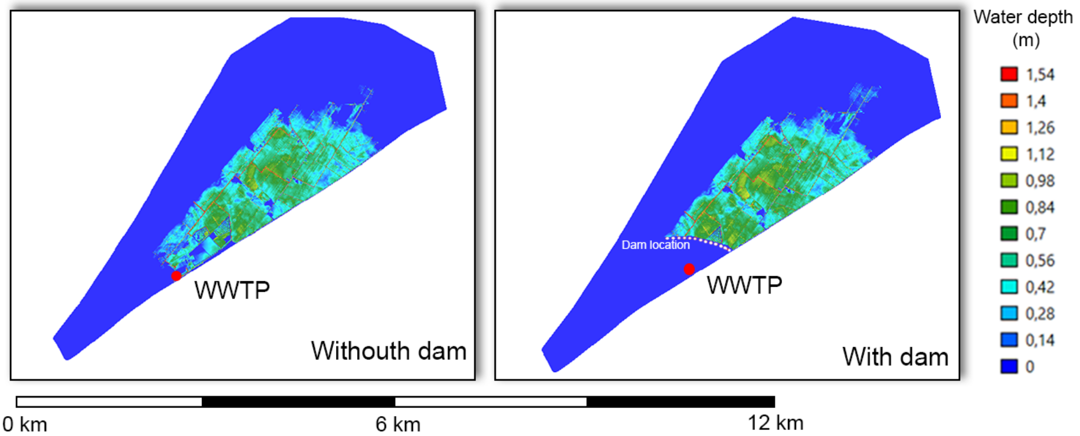


Figure 26: Results for study area 3 with flooding in region near WWTP without a dam (left), and with a dam (right)

From Figure 26 it is clear that the dam has a big impact on the flooded area. It prevents water from spreading further south and expands the inundated area in the North. The dam should not only be added to model to see the ability to protect the WWTP, but it should also be added to see the side effects of adding a dam.

5.2.6. Weirs

The possibility of adding weirs to the simulation has been examined, however, for multiple reasons, this would be really time consuming. Since it is not expected to have a significant effect based on other tests, the addition of weirs has not been tested. The reasons for the difficulty are: 1. Weirs are mapped as point features; D-HYDRO requires line features. It currently is difficult to translate these point features into a correct line with proper length and direction. This would be really time consuming and the result would probably not be very accurate. 2. Also D-HYDRO currently does not give an option to load in the height value of a weir, this means this would have to be done manually.

The functioning of the weir function is tested and works as expected. If big weirs that are expected to have a big influence on the results are present in the area, it is advised to add them manually. Also, for 1D2D couples models it is advised to add weirs, since this is easier with 1D models, and the correct data is available.

5.2.7. Angular grid

D-HYDRO provides to ability to make a rectangular grid at different angles. In this test it is checked whether a different angle on the grid causes a difference in results. It is expected to not make a difference at fine grids. Ideally, results would be identical with both grid angles, since this implies the model is robust.

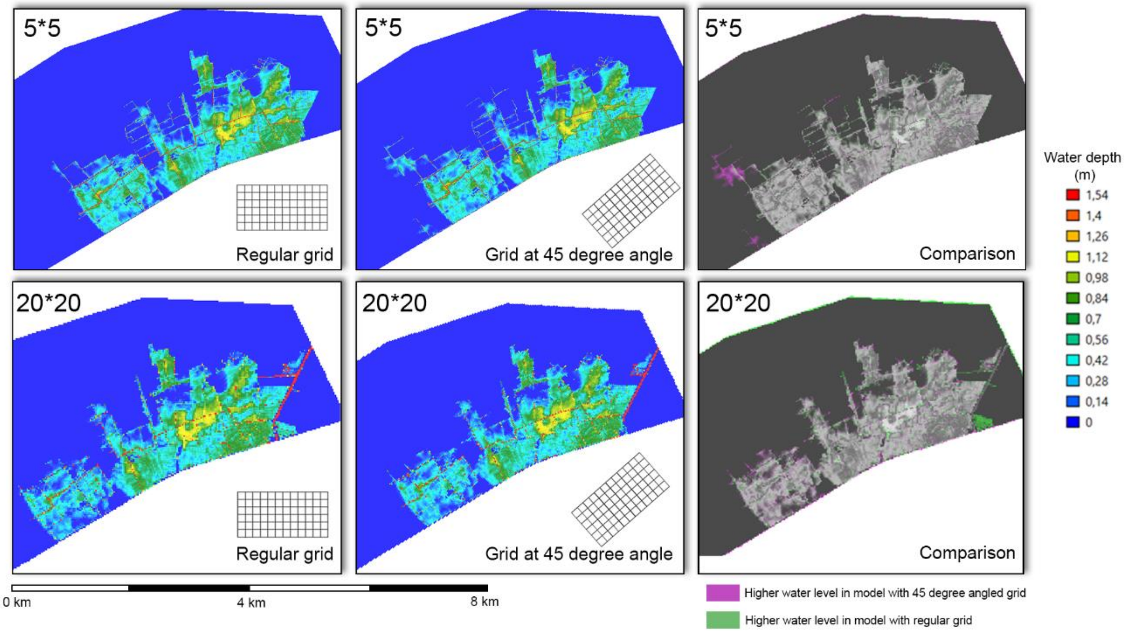


Figure 27: Results for study area 1 with regular grid (left), with angular grid (middle), and their comparison (right).

From both the comparisons in Figure 27, we can see that constructing a grid at a 45 degree angle has influenced the inundated area. At both the 5*5 and 20*20 resolution, a small change in results is noticeable.

A reason for this change could be that the grid is interpolated differently. With a different grid angle, grid cells contain different samples. These samples are averaged out over the grid cell. It could be that because of this, certain elevation data is represented differently when the grid resolution changes.

The difference between a regular grid and an angled grid is only small, so the results of this test still show that the model is robust. However, it should always be considered that a model can give different output solely based on a difference in grid orientation. This is a change that is not based on any changes in input data. Changes in results like these have to be considered by giving an uncertainty range for the model.

Table 13: Computation and set up time for model with an angular grid.

Model (area 1)	Computation time (hh:mm:ss)	Set up time
Regular grid	04:40:15	Regular set up time
Angled grid	04:39:15	Regular set up time

From Table 13 it can be seen that the computation stays the same, which was expected. The 2 models have similar area characteristics, amount of grid cells, inflow, and inundated area.

5.2.8. Model size

From the previous test, it became clear that the total amount of water in the system has a significant effect on model computation time. This is because with more water, the inundated area gets larger, this causes more required computations per time step.

It is interesting to know whether an increase in the total area of the modelled area would affect computation time. To test this, the basic model of study area 1 at 5*5 has been run to simulate 6 hours of inundation. The results are compared to a model with only the size of the flooded area after 6 hours. The size of the 2 models can be seen in Appendix K: Model size.

All models provided the exact same output, as is expected since only the area that is not affected was changed. Only the smallest area of 3.5 km^2 was a bit smaller than the inundated area, and thus had a slightly different inundation pattern. The computation time for the different models can be seen in Table 14. From Figure 28, it is clear that there is a relationship between area size and computation time

Table 14: Computation time and estimated amount of grid cells for model areas with different sizes.

Area	Surface area km^2	Estimated grid cells	Computation time (hh:mm:ss)
Smallest	3.5	140000	00:16:47
Small	5.63	225200	00:23:29
Medium	8.47	338800	00:32:59
Large	13.2	528000	01:02:20*
Original	18.6	744000	01:00:19

** The large area seems to be a bit of an outlier in terms of computation time, but it has been tested twice with similar results both times.*

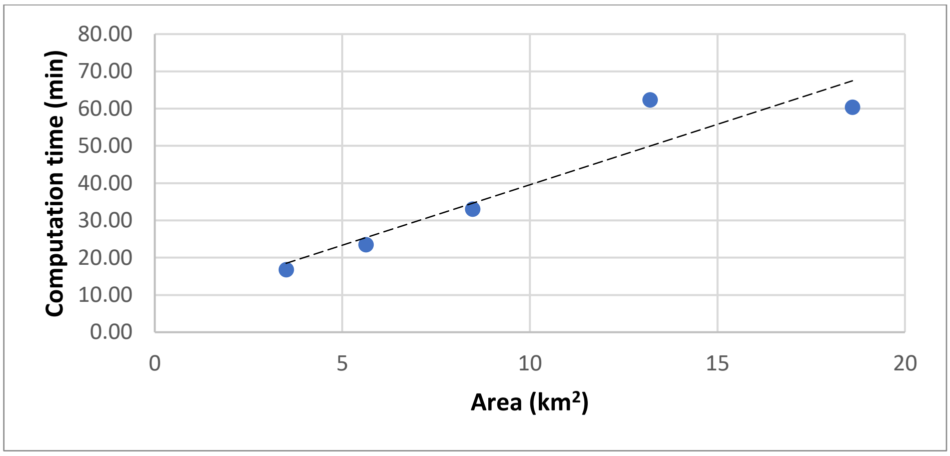


Figure 28: Relation between model area size (km^2) and computation time (minutes)..

To conclude, model size does affect computation time. Ideally, the model size should be as close as possible to the inundated area of the model. With this, no time is wasted on dry cells that do not have an influence on inundation. However, in practice it is difficult to estimate the inundated area before running the model. A method to overcome this is to first run a simulation on a coarse grid and determine the area size based on these results. However, because this takes time to set up, it is only worth the effort if the final model has a long computation time.

5.2.9. Initial water levels

Adding additional water levels causes water ways to be filled before the simulation has started. This is a more realistic representation of the real world. To test the effect of adding this, winter target water levels are added to the model. These water levels are location dependent, based on the monitoring areas.

Adding an initial water level has been tested both with and without culverts. From chapter 5.2.1 it became clear that adding culverts can have significant effect on water flow through waterways. Without culverts, some waterways are not connected, hindering the spread of the water over the area. The results can be seen in Figure 29.

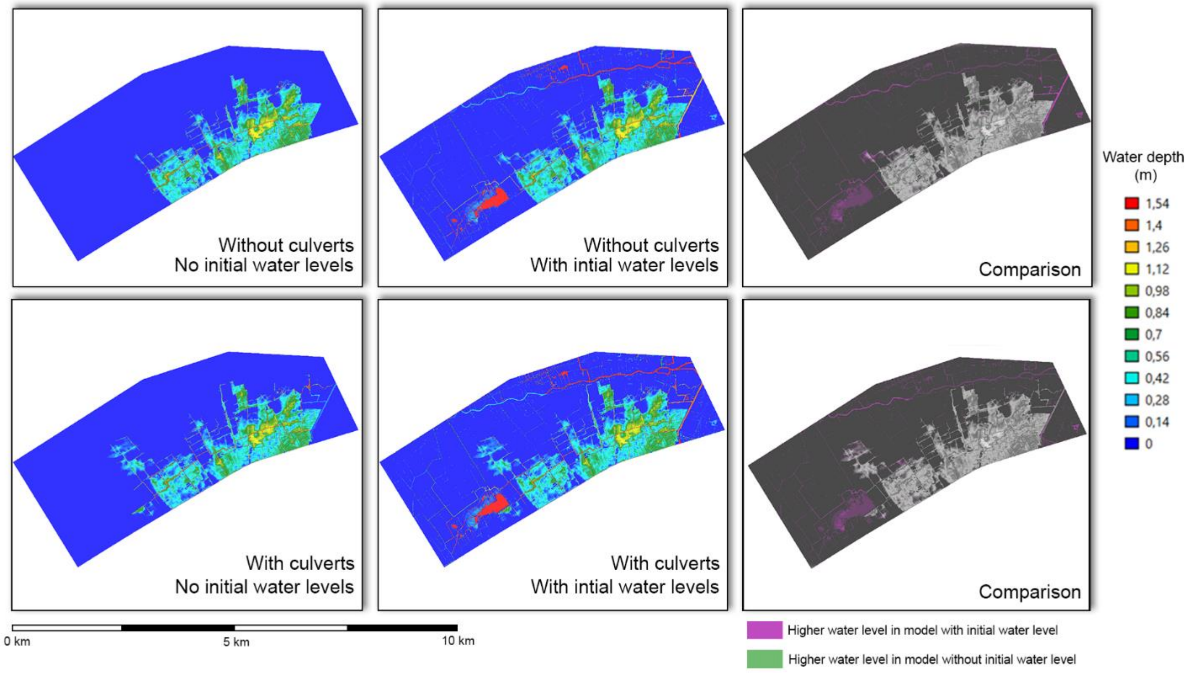


Figure 29: Study area 1 with and without an initial water level. No culverts (top) and with 6 meter wide culverts (bottom) have been tested.

Logically, adding initial water levels has a lot of effect on the water depth in the area. Waterways that were empty are filled up by using initial water levels. This can be seen in the results. The inundated area barely changed after 24 hours. The same tests have also been performed for study area 2, with similar results. The results can be seen in Appendix L: Initial water levels.

However when looking at the results after 6 hours, a bigger difference in inundated area can be seen. The results at 6 hours can be seen in Figure 30. This shows that adding an initial water level has an impact on inundated area.

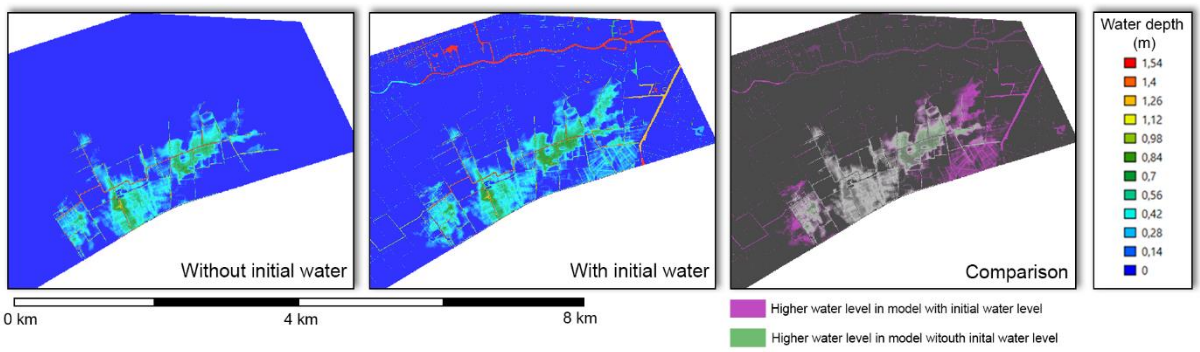


Figure 30: Results after 6 hours for study area 1 base model (left) and with initial water levels (middle), and a comparison (right).

Table 15: Computation time with initial water levels.

Model	Computation time study area 1 (hh:mm:ss)	Computation time study area 2 (hh:mm:ss)
Base model	04:40:15	01:14:03
With initial water levels	05:04:16	01:20:25
With initial water levels and culverts	05:02:23	01:22:43

In Table 15 the computation times can be seen. From the results, there seems to be a slight increase in computation time caused by adding initial water levels. This is logical, as there is a higher number of wet cells, and thus more computations have to be done for these cells.

Even though the differences for the tested models were sometimes small, it is still advised upon including water levels when possible. It is not a requirement; however, it is an improvement to the model. Also, in certain situations, adding the water level can be more important. For example if a lake is located in the model, without initial water levels, the lake has a much larger capacity to retain water. In this case, adding initial water would significantly impact the results, as less water can be retained in the lake since it already contains water from the start of the simulation. If water levels are ignored, the Hoeksmeer lake has an additional capacity of 741600 m^3. Such storage can have significant effect on model output. It has to be considered that during an actual dike breach, the water levels within the area could be higher than the target winter water levels.

5.2.10. Breach inflow

Breach inflow is a very important part of the simulation, but within flood modelling it is almost always an uncertainty (Blazkova & Beven, 2009). The breach determines the amount of water that enters the system, and this can affect results significantly. It is important to get an understanding of how different methods of implementing breaches behave in D-HYDRO.

For all other tests in the sensitivity analysis (chapter 5.1 and 5.2), a constant fixed inflow has been used. For the comparison to TYGRON in chapter 5.3, a slightly different approach is used, which is explained in chapter 5.3. The following section describes the other possibilities of modelling breach inflow.

Breach modelling methods

3 different methods have been tested to simulate a dike breach and the inflow. Method 1 and method 2 both use the boundary inflow option from D-HYDRO. Method 3 is modelling the Eemskanaal and connecting it to the grid of the inundated area via a dike breach.

Appendix M: Breach inflow, contains the detailed tests performed on the different breach inflow methods. It is strongly recommended reading this appendix if you plan on using D-HYDRO for flood simulations. Because of the length, this section has been moved to the appendix. It contains test results for all 3 methods, and a comparison between method 2 and 3. This appendix gives a good view of the current complications regarding breach inflow in D-HYDRO.

Method 1: Fixed inflow

This is the method that is currently used throughout the sensitivity analysis. Based on the location, size and inflow of a dike breach, D-HYDRO determines where water is added in the system. The amount of water is specified by the user. The advantage of this method is that the user can have a clear environment and it is known how much water enters the system. That is also the reason why this method is used throughout the sensitivity analysis, it provides a consistent output for comparisons.

The disadvantage of this method is that it is somewhat unrealistic. In real life, the inflow depends on the water level, bed level and breach size. These variables can change over time. By using a fixed inflow, these

3 variables are estimated in order to estimate an inflow. As the water in the inundated area rises, D-HYDRO keeps forcing additional inflow in the model. Inflow can be predicted ahead of time; however, this takes additional time.

Method 2: Specified water level

The second method is specifying the water level of a dike breach at a certain location and with a certain size. From these characteristics, and with the bed level, D-HYDRO determines how much water flows through the dike breach. This is more realistic and dynamic than a fixed inflow.

Currently there is no method to make the water level depend on the amount of water that has flowed from the source (Eemskanaal) to the rest of the model. Water level can be varied over time, but the user has to determine the water level before the start of the simulation. This is no problem in case the inflow is small compared to the volume of the source. However, in the case of the Eemskanaal, the water level lowers quite quickly due to the inflow. This change in water level is not taken into calculations by D-HYDRO and is difficult to predict before starting a simulation. This is a big disadvantage, and a feature that should be added to D-HYDRO.

Another important note is that the breach size can only be a multiple of the grid size. A breach inflow boundary condition with width 2 meters on a 20 meter grid becomes equal to the grid size of 20 meters.

Method 3: Modelling the water inflow channel

The third method is modelling the Eemskanaal within the D-FLOW FM model, and connecting it to the grid. This provides the most realistic results, as the water flow from the Eemskanaal to the flood area is considered in the model. However, it is hard to set up compared to the previous methods. Also, the dike breach size and location are not as customisable since the dike breach has to be a grid connection. It can be tricky to create a grid connection between the Eemskanaal and the study area, and a careful approach is required to have a similar outcome each time. Also, D-HYDRO is unstable while working with multiple grids, 10*10, and 5*5 models both crashed at various stages. Therefore only 20*20 models are tested for this method.

Breach discharge

Figure 31 shows the relationship between computation time and breach inflow. The relationship is linear, with greater inflow leading to higher computation times. The increase in computation time is a combination of 2 factors. Firstly, greater inflow results in higher velocities, which results in a smaller time step and thus longer computation time. Secondly, with greater inflow more cells are inundated, and thus more calculations have to be performed. These simulations are done with breach method 1, in order to provide consistent results.

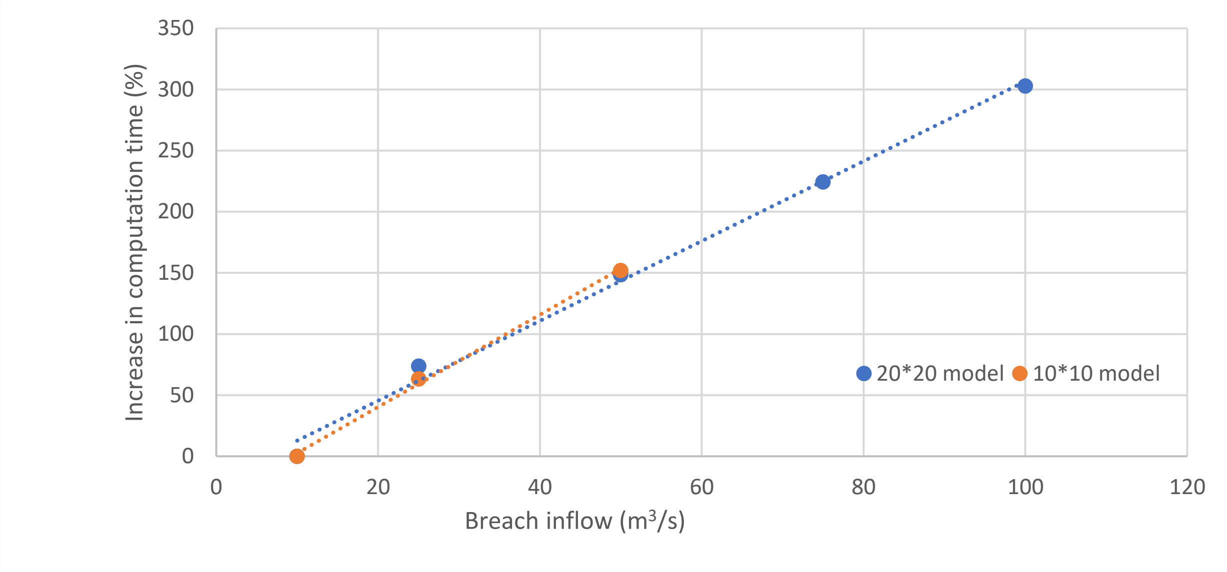


Figure 31: Computation time increase in % for different breach inflows, breach inflow of 10 m^3/s is used as a base computation time.

Within this chapter, multiple methods that have been found within the software to model a dike breach have been tested. In a conversation with Deltares in week 6 of the 10 week period at the waterboard, an additional method to model dike breaches in D-HYDRO was discovered. Adding a so called "levee breach" on a fixed weir. This method incorporates more calculations about how a dike breach develops over time according to physical calculations about the dike breach (Verheij & Knaap, 2003). However, after many tries, the function has not worked properly for the simulations in this research.

Limited time was left for the research. For the comparison between D-HYDRO and TYGRON, the function was not going to be used since it does not provide enough user control for the inflow. Therefore, no further research has been done on this function. Both because of the limited time and because the function will not be used further in this research. For the waterboard it is recommended to do additional research on this function as it simulates the dike breach more accurately than the functions used in this report. It requires some additional set up time, but it is used by Deltares in the current D-HYDRO release. If the method were known earlier, it would have been interesting to make the comparison to the other methods.

5.2.11. 1D2D modelling

1D2D modelling couples a 1 dimensional model to a 2 dimensional model. Within the 1 dimensional model, water flowing through water channels can be calculated quick and accurately. When water does not fit in the 1D channels, the water channel overflow and the 2d model is used to calculate inundation on land areas.

Unfortunately, with the current release of D-HYDRO, 1D2D modelling within D-HYDRO does not work properly yet. This feature is still in development. Importing 1D models from SOBEK should work according to Deltares. However, it is not feasible to learn a new software package in such a short period of time just for the function of 1D2D modelling. For this reason, 1D2D modelling has not been tested. When this function gets updated, it is a promising feature that could be beneficial to flood modelling. 1D models are faster than 2D models, and by combining the two, the computation time is expected to go down. Also, 1D modelling provides additional accuracy in the water channels since cross sections can be imported. This provides detailed information about water channels, which would be lost in the 2D model, because the 2D model has such a large grid cell size. Also, with the large grid cells, waterways can be averaged out, and even more details are lost. This detail would be maintained in if a 1D model would be combined with a 2D model.

5.3. Comparing D-HYDRO and TYGRON

In order to compare TYGRON and D-HYDRO to each other, 3 flood simulations performed in TYGRON are replicated in D-HYDRO. The flood simulations in TYGRON have been performed by the waterboard in 2019. The dike breach locations and the corresponding study areas can be seen in Figure 32. These dike breaches have been selected since these provide the best output to compare to D-HYDRO.

In TYGRON, about a third of the entire management area of the waterboard is set up in a single model. This makes it easy to make simulations of multiple dike breaches at different locations, since this can all be done in the same model. This is not possible in D-HYDRO, since the computation would take very long. Therefore, in D-HYDRO, a new model has to be set up for the different study areas.

TYGRON has a resolution of 1*1 meter, this is a lot more detailed than the D-HYDRO models of the same areas. The D-HYDRO models range from 100*100 to 10*10 meter. The exact computation times for the TYGRON models are not available since this data is not recorded at the time of performing the study. The computation time was in the range of hours. TYGRON can get such fast computation times on a large model because calculations are done on a supercomputer. More about this can be read in Appendix A: Model computation time.

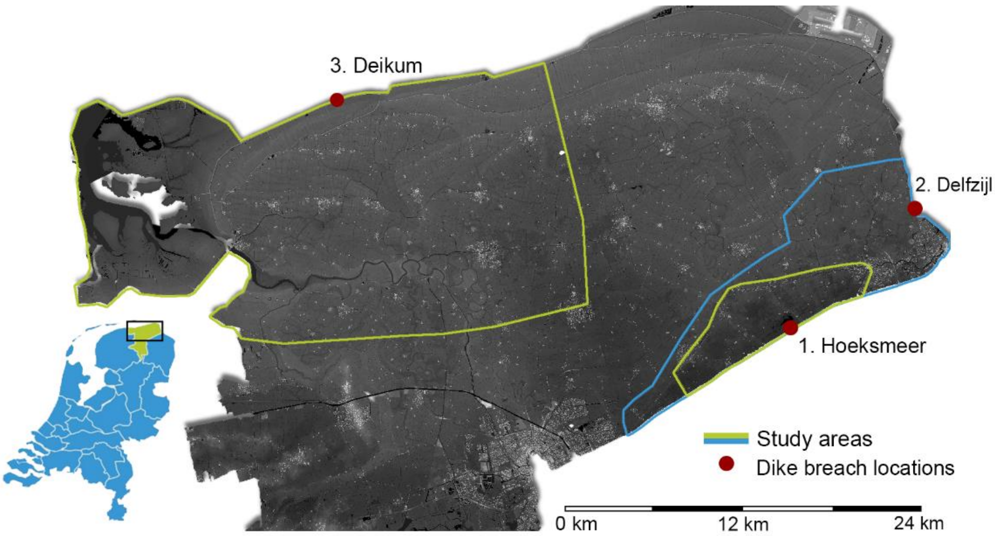


Figure 32: Dike breach locations and corresponding study areas that are used for the comparison between D-HYDRO and TYGRON.

Model replication

From the model study in TYGRON regarding the climate stress tests, only images of the water depth after the entire simulation period are available. Therefore, the water depth after 4 simulation days is compared. As mentioned earlier, D-HYDRO and TYGRON use different methods to calculate the discharge through a dike breach. Therefore, even with similar dike breach characteristics, the output total inflow from the dike breach can vary significantly. In order to make a good comparison, the dike breach inflow from the TYGRON models has to be replicated as accurately as possible. This way, the comparison can be focussed on the flood propagation.

Firstly, to get a good estimate on the total inflow from a dike breach, a Python script has been made. This script takes the image with the water depths as an input. From this image, the script estimates the total water in the system.

Knowing an estimated total inflow, calculations can be done for the actual inflow over time. This is done prior to the simulation. The same formulas that are used in TYGRON are also used in D-HYDRO, to ensure the breach discharge is similar to TYGRON's breach discharge. This is done according to equation 9 (TYGRON , 2019). TYGRON bases the dike breach discharge on the weir formulas.

$$C_{free} = f_{w,d} * c_w * w_w * (h_s - h_d)^{\frac{3}{2}} \tag{9}$$

Where C_{free} is the discharge through the dike breach, $f_{w,d}$ is the Dutch weir factor, c_w is the weir coefficient, w_w is the width of the dike breach, h_s water level outside the breach and h_d is the water level in the flood plain, or the breach level. In Figure 33 there is a visualisation of the measurements of such a dike breach.

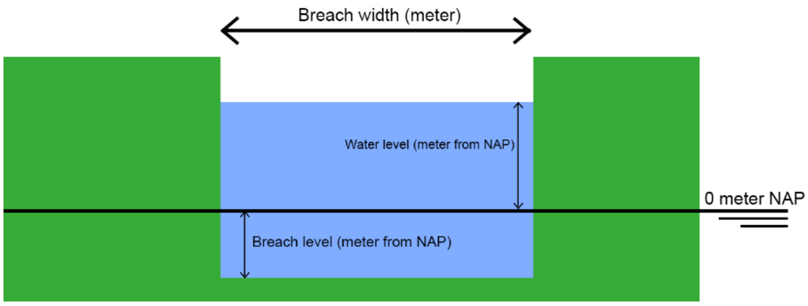


Figure 33: Front view of a dike breach with measurements.

With equation 9, the discharge through the dike breach per time step is calculated. Also, the total inflow over the entire simulation period is calculated. Input variables that are not known from the simulation in TYGRON are modified until the total inflow is similar to the estimated total volume calculated by the Python script. With the corresponding discharges per time step calculated, a first low resolution model has been run. The output is compared to the TYGRON simulation, to see if a higher or lower discharge is required. A flowchart of the whole process can be seen in Figure 34. The disadvantage of this method is that results at a low resolution are not always the same as results at a high resolution.

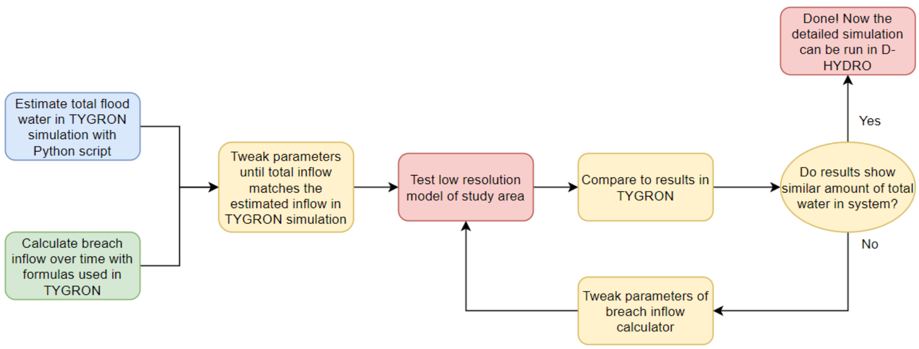


Figure 34: Flow chart of actions performed to determine the dike breach discharge. Blue = Python, Green = Excel, Red = D-HYDRO, Yellow = user action.

Interpretation of results

The output available from the TYGRON models is an image, with a legend that separates the water depth in different classes (for example see the top left of Figure 35). These classes are not distributed evenly. For this reason, it is not possible to make a figure showing the difference in water depth between the simulations. Therefore, a different method is used to compare the results of the D-HYDRO simulation to the results of the TYGRON simulation.

The method of comparison that is used in this study is based on the inundated area. With a Python script (Appendix N: Python script for image analysis), the images of the results are compared to each other on a pixel level. The python scripts detect if an area is inundated, or not inundated. It does this for both the image of the TYGRON simulation, and the image of the D-HYDRO simulation. For every pixel, the result is compared. There are 4 possible conclusions, these are listed in Table 16.

Table 16: Possible conclusions per pixel (or area) from image comparison.

Situation	Interpreted as
D-HYDRO calculated the area as inundated, TYGRON calculated the area as dry.	Miss
TYGRON calculated the area as inundated, D-HYDRO calculated the area as dry.	Miss
Both D-HYDRO and TYGRON calculated the area to be inundated.	Hit
Both D-HYDRO and TYGRON calculated the area to be dry.	Not taken into account

With this data, the accuracy of the D-HYDRO simulation in comparison to the TYGRON simulation can be calculated, according to equation 9.

$$Similarity\ (\%) = \frac{Hits}{(Hits + \ Misses)} * 100 \tag{9}$$

Results for the different study areas cannot be compared to each other. The accuracy is heavily dependent on the inflow. If the D-HYDRO simulation has either more or less inflow than the TYGRON simulation, the resulting inundated area will differ. Therefore, the accuracy is dependent on how good the estimation of the inflow is. This is done separately for each study area, and thus different study areas should not be compared. Different models for the same study area can be compared since they all have the exact same inflow.

Dike breach location 1: Hoeksmeer

This location concerns a dike breach in the dam of the Eemskanaal. The breach width is 10 meters. As water flows through the breach, the water level in the Eemskanaal lowers. For these simulations, the breach is closed after two days. The simulation period is four days, this means that after two days, there is not additional inflow, but the water can still spread. The outcome of the estimation of the dike breach characteristics (Figure 34), is an initial water level in the Eemskanaal of 1.9 meters NAP, and a breach level of -1.6 meter NAP.

Six different models have been tested for this dike breach location, with different grid resolutions. The first four are regular grids, with sizes 10*10, 20*20, 50*50, and 100*100 meters. The other two are flexible mesh grids. A 50*50 grid that is refined twice at 300 meters around the main waterways. And a 20*20 grid refined ones at 80 meters around the main water ways. In Figure 35, the output for the 10*10 meter model compared to TYGRON can be seen. The results for the other models can all be seen in Appendix O: Hoeksmeer.

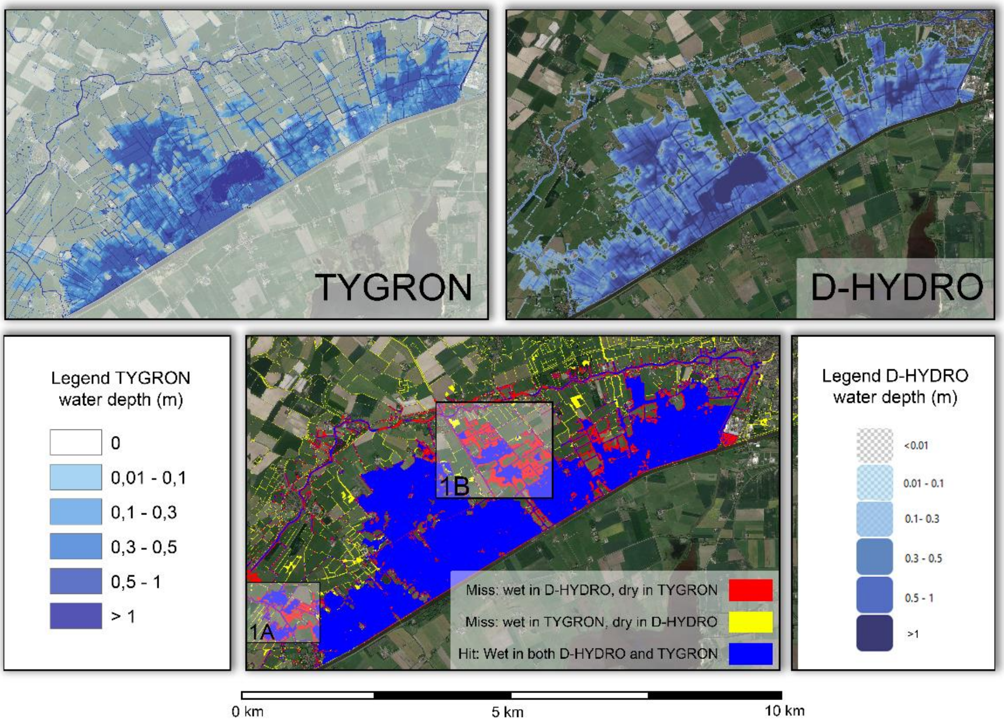


Figure 35: Results after 4 simulation days of D-HYDRO at 10*10 meter resolution compared to results after 4 days in TYGRON at a 1*1 meter resolution. Results for dike breach location 1: Hoeksmeer.

From Figure 35 it can be seen that the overall inundated area is really similar in both models. Even though the grid size is ten times larger in D-HYDRO, the inundated areas are really similar. Overall, D-HYDRO seems to overestimate the inundated area compared to TYGRON. However, it is hard to say whether this is due to a different dike breach discharge, the grid resolution, or something else. Especially in locations 1A and 1B D-HYDRO overestimates the inundated area. However, it calculated a very low water depth at these overestimated locations.

Most locations where TYGRON calculated inundation and D-HYDRO did not, are waterways. This has a logical reason: D-HYDRO grid cells are significantly larger than many of these water ways.

Table 17: Results comparing D-HYDRO to TYGRON for dike breach location 1: Hoeksmeer.

Model	Similarity to TYGRON	Computation time (hh:mm:ss)
100*100	50.4%	00:00:27
50*50	60.3%	00:03:22
50*50 with 2 refinements around main waterways	66.1%	00:25:54
20*20	67.6%	00:49:10
20*20 with 1 refinement around main water ways	69.1%	01:44:24
10*10	74.4%	08:57:22

From Table 17 it can be seen that similarity increases with more detailed grids. However, this comes at the cost of computation time. Also, it can be seen that flexible mesh improves similarity significantly, the 50*50 model with 2 refinements is close to the similarity of the 20*20 model. The computation time for the flexible mesh model is half. Also, it can be seen that big grid cells perform reasonably well within a very short computation time.

Surprisingly, the 20*20 model with 1 refinement does not perform as well as expected. The reason for this is that this model calculated higher water depths in region 1A (Figure 35). This is surprising, since both the 20*20 and the 10*10 model do not calculate this. This miscalculation causes the lower than expected similarity of the 20*20 flexible mesh model. At all the other locations, the 20*20 flexible mesh simulation with 1 refinement performs very similar to the 10*10 model, within a fraction of the computation time.

Dike breach location 2: Delfzijl

This location concerns a dike breach in the dike of the Waddenzee. The breach width is 50 meters, which is much larger than at the previous location. A constant water level of 4.83 m NAP is assumed. The dike breach height is assumed to be 3 meters, which follows from the process described in Figure 34. The total simulation period is 4 days, after 2 days, the dike breach is closed. Therefore, there is no inflow through the dike breach after 2 days.

6 models have been tested. 4 of them have regular grids with resolution of 100, 50, 20 and 10 meters. 2 of them have flexible meshes. The first has a 50 meter grid, with 1 refinement at 200 meters main water ways (so a resolution of 25 meters at main water ways). The second has a 20 meter grid, with 1 refinement at 80 meters around the main waterways. The results for the 10 meter grid compared to the TYGRON simulation can be seen in Figure 36.

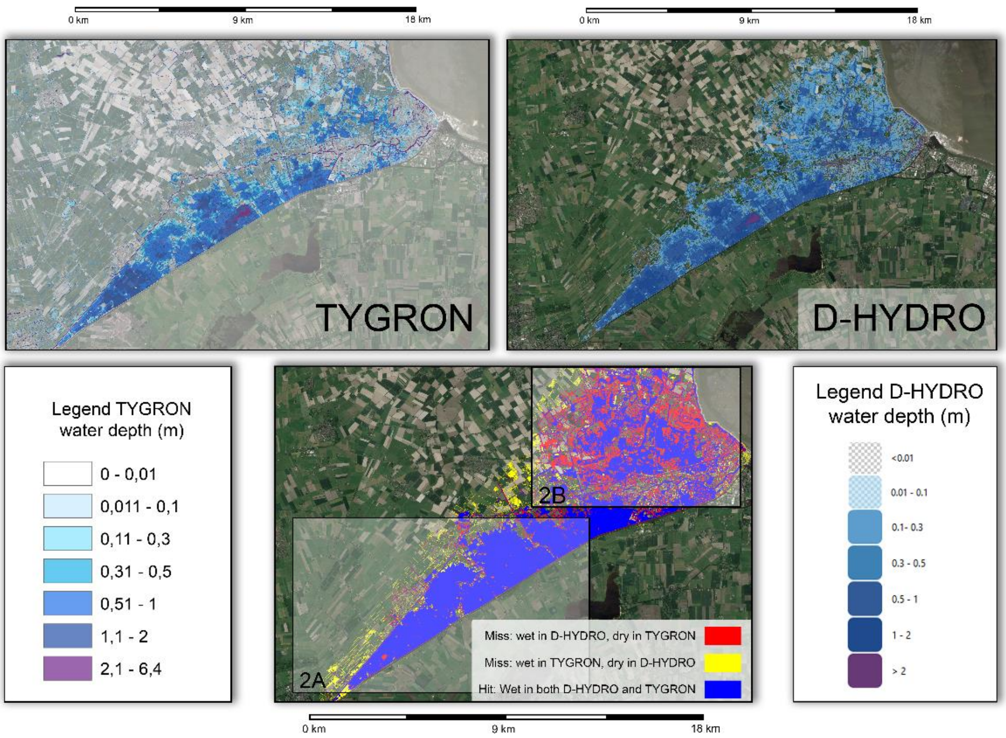


Figure 36: Results after 4 simulation days of D-HYDRO at 10*10 meter resolution compared to results after 4 days in TYGRON at a 1*1 meter resolution. Results for dike breach location 2: Delfzijl.

In Figure 36 it can be seen that again; results are relatively similar in TYGRON and D-HYDRO. However, D-HYDRO overestimated the flooding in area 2B in comparison to TYGRON. This could be because of a higher breach inflow. It also could be because of the larger grid size, which generally causes overestimations in areas with a lot of height variation. But when looking at the overall flood propagation, both models perform relatively similar. Especially area 2A is similar. In Table 18, a comparison between all the different simulations that are performed in D-HYDRO can be seen.

Table 18: Results comparing D-HYDRO to TYGRON for dike breach location 2: Delfzijl.

Model	Similarity to TYGRON	Computation time (hh:mm:ss)
100*100	56.8%	00:02:22
50*50	58.7%	00:19:18
50*50 with 1 refinement around main waterways	59.3%	02:03:16
20*20	63.9%	07:53:51
20*20 with 1 refinement around main water ways	65.4%	15:44:01
10*10	66.1%	71:30:07

The images of the results for the simulations at different resolutions can be seen in Appendix P: Delfzijl. From the results it can be seen that similarity increases with smaller grid cells, but so does the computation time. The 10*10 model took almost 3 days to run, this is 9x as long as for Hoeksmeer. This is because at the dike breach location in Delfzijl, there is much larger inflow, and thus larger flooded area. The 100*100 model is very rough, however still gives a good insight on the overall flooded area, and it does so within 3 minutes of computation time. This shows the potential of models with large grid cells. The Flexible mesh models performed very well. Especially 20*20 with 1 refinement shows a significant increase in accuracy with a relatively small increase in computation time.

Dike breach location 3: Deikum

Dike breach location 3 again concerns a dike breach in the dam of the sea. The breach width is 50 meters. A constant water level of 4.83 m NAP is assumed. The dike breach height is assumed to be 1.5 meters, which follows from the process described in Figure 34. The total simulation period is 4 days, after 3 days, the dike breach is closed. Therefore, there is no inflow through the dike breach after 3 days.

6 models have been tested. 3 of them with regular grids and grid sizes of 100, 50, and 20 meters. And 3 flexible mesh models. The first flexible mesh model has a base grid of 50*50 and has 1 refinement at 200 meters around the main waterways. The second flexible mesh model is also based on a 50*50 meter grid and has 2 refinements at 300 meters around the main waterways. The third is based on a 20*20 model with 1 refinement 80 meters around the main waterways.

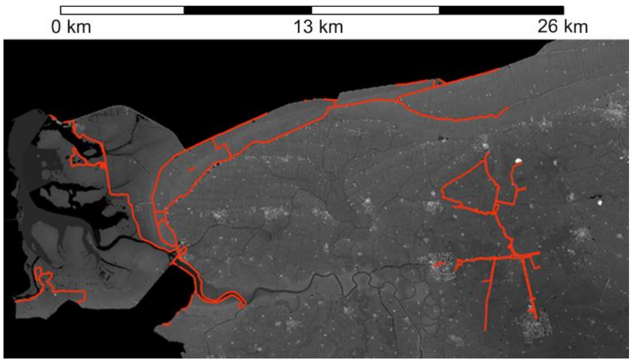


Figure 37: Dikes that have been manually added to the D-HYDRO model of dike breach location 3: Deikum.

In contrast to the previous two locations, there are a lot of important dikes in this region that have a big influence on the results of the simulation. In TYGRON, these dikes are represented on the grid since the grid resolution is sufficiently small with 1*1 meter. In the D-HYDRO model, this is not the case, since larger grid cells are used. Therefore, dikes have been added manually to the model. The location of the dikes that have been manually added to the model can be seen in Figure 37. In the current release of the D-HYDRO beta, it is not possible to automatically add dike heights yet. Therefore, this has been added manually. A constant height over the entire length of a dike has been assumed. This is not realistic since the dike height will always vary based on the location. In TYGRON, this variation is included since the dike is represented within the grid cells. This is not the case in the D-HYDRO model. Because of this inaccuracy, there is an additional difference in results between the D-HYDRO and the TYGRON model results.

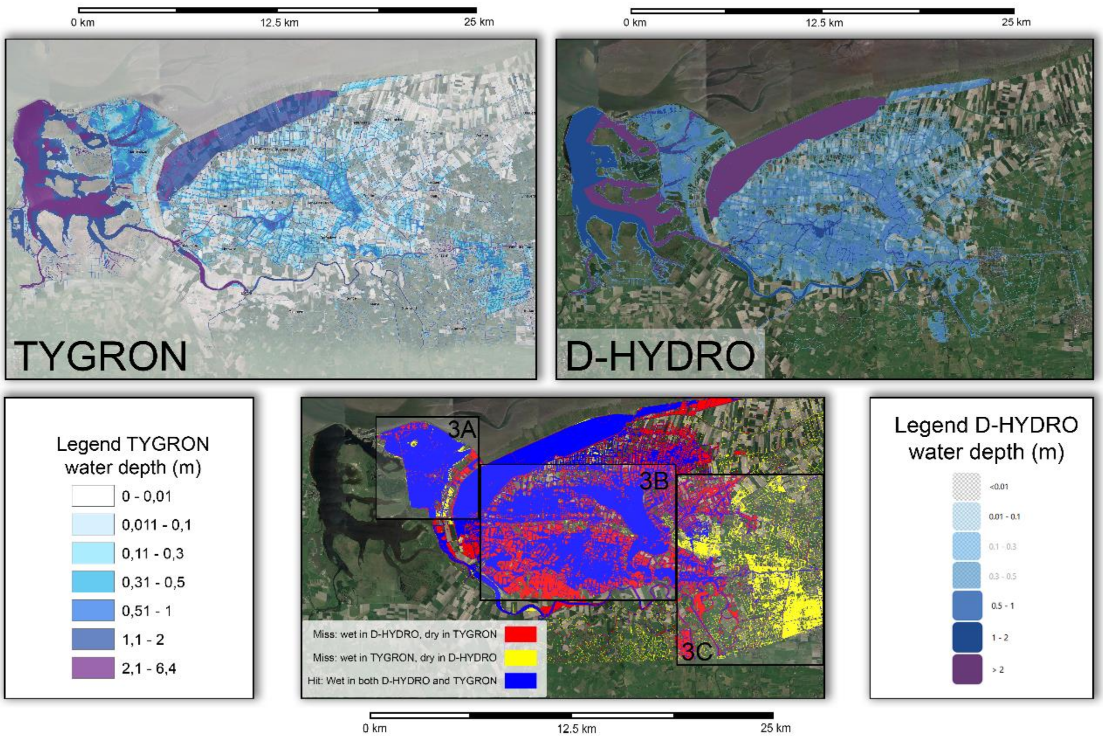


Figure 38: Results after 4 simulation days of D-HYDRO at 20*20 meter resolution with 1 refinement 80 meters around main water ways, compared to results after 4 days in TYGRON at a 1*1 meter resolution. Results for dike breach location 3: Deikum.

In Figure 38, the results for simulations are shown. Comparing the results of D-HYDRO and TYGRON, there are more differences than at the previous 2 comparison locations. In area 3C, D-HYDRO barely calculated any inundation, while in TYGRON, there is a large inundated area. There are multiple causes that could contribute to this different estimation. It could be that because of the grid size, waterways are not represented, and water does not travel through these waterways. It could also be, that there is a lower dike breach inflow in D-HYDRO, however this seems unlikely because of the overestimation in inundated area in area 3B and 3A. It could also be, that since D-HYDRO has a constant height over the length of a dike, that the dike overtops at different locations. This causes differences in inundated areas.

The other 2 simulations were no perfect matches, but the overall inundated area was relatively similar for TYGRON and D-HYDRO. This is not the case in this simulation. Despite this, the simulations are still relatively similar, apart from area 3C. The results for the different simulations performed in D-HYDRO can be seen in Table 19.

Table 19: Results comparing D-HYDRO to TYGRON for dike breach location 3: Deikum.

Model	Similarity to TYGRON	Computation time (hh:mm:ss)
100*100	50.3%	00:04:42
50*50	52.0%	01:16:31
50*50 with 1 refinement around main waterways	53.0%	03:13:10
50*50 with 2 refinements around main waterways	54.5%	14:44:50
20*20	56.0%	31:41:37
20*20 with 1 refinement around main waterways	57.5%	46:54:24

In Appendix Q: Deikum, images of the results of all simulations can be seen. From Table 19, similar conclusions can be drawn as for the previous dike breach locations. Again big grid cell simulations perform very well compared to the smaller grid cell simulation. Within just a fraction of the total computation time the Flexible mesh models performed as expected. They provide additional accuracy while having a lower computation time.

6. Discussion

6.1. Discussion of the findings

The study has shown how different model components can affect the simulation output and computation time. The advice given in this research is based on multiple simulations per variable. Within these simulations, it is not possible to test for every possible scenario since the possible scenarios increase exponentially with the number of testing parameters. Recommendations are based on the simulations for specific case studies and should be used with caution for other cases. Therefore, it is always up to the user what to include and what not to include. Especially for urgent simulations, it can be beneficial to leave out certain model components.

The comparison between D-HYDRO and TYGRON has shown similar results for both software packages. However, an uncertainty in the comparison is the inflow of water through the dike breach. Some of the differences between the simulations are caused by a different inflow, rather than a different simulation of the flood propagation. Also, the TYGRON simulations have a much smaller grid size, which results in more detailed simulations. That being said, the comparison still shows a similar flood propagation for both software. The comparison to TYGRON provides a good benchmark to test different D-HYDRO models. However, it should be considered that TYGRON is just a different simulation, and not a perfect representation of reality.

Over the course of this research, more skill is developed with the D-HYDRO software package. This causes some differences in setting up simulations in the beginning compared to the end. The overall simulations are not changed, but sometimes computation times for early performed tests could be slightly longer than they actually should be. This is for multiple reasons, the main one being that at the time it was not known that D-HYDRO should frequently be restarted to ensure the software does not get slower. However, these are minor effects. The computation times have all been checked for validity, and if computation time was different than expected, the simulation was done again. Also, inundated areas were not recorded at the start of this research, inundated areas have been calculated later based on image analysis.

At the time of performing this research, D-HYDRO is still in a beta stage. The core functionality works is finished, however some details about D-HYDRO are likely to change.

6.2. Limitations of the research

This research is finished within 10 weeks. It would be interesting to see how more detailed simulations in D-HYDRO increase the accuracy and computation time. It would also be interesting to know computation time at better computers and possibly a computer cluster. With the current hardware and limited time this has not been possible. With this information, the waterboard could make better decisions on which hardware to invest in.

Some of the tested model components have not been tested fully because this was not possible due to software problems. The most important component that has not been tested is 1D2D modelling. 1D models made in D-HYDRO could not be coupled with a 2D grid. Deltares mentioned that importing SOBEK models should work. This is an interesting topic to research further.

The results of this study are applicable to other regions than the tested areas. However, when doing so, the area characteristics of the tested study areas should not be disregarded. For example: when making simulations for an area with mountains, results could be different.

As mentioned in the report only images of the results of the TYGRON simulations were available. This caused some limitations for the comparison, since only images of the results could be compared. If the entire TYGRON model was available, a much better estimation of the inflow could have been made. Also, a better comparison could have been made that included the actual water depths per location.

7. Conclusion & Recommendations

7.1. Research question 1: How do different model components affect accuracy of a D-HYDRO model? & Research question 2: How do different model components affect the computation time of a D-HYDRO model?

A summary of the conclusions based on both the sensitivity analysis and the comparison with TYGRON can be seen in Table 20. These conclusions answer both research question 1 and 2. When making a detailed simulation, it is advised to follow the information in this table to set up a D-HYDRO model. However, when making rough simulations with very short computation times, it is not always worth the additional set up time to add all of these variables. For rough simulations with computation times under 5 minutes, it is not worth it to add any additional input data other than the DEM, an appropriate grid size, and a good estimation of the dike breach.

Furthermore, it is advised to set up a rough 100*100 model for the entire management area of the waterboard. This model can function to quickly model a dike breach, to get an estimation for the flooded area. This area can then be used in a more detailed model.

Table 20: Conclusions on different model components based on the sensitivity analysis and the comparison with TYGRON.

Model component and chapter	Effect on inundation mapping	Effect on computation time	Required data/ set up time	Recommendation
Grid size 5.1.1 and 5.3	Significant effect on inundation, smaller grid cells result in more detail in the simulation. However large grid cells still provide reliable results.	Significant effect on computation time. By halving the length of a grid cell, computation time can increase by 10 times.	Same data required, but smaller grid cells require a more detailed DEM. With more grid cells loading times can be longer.	Fit grid size to what is required from the model. If fast output is required, use a large grid cells. If more detailed output is required, use smaller grid cells.
DEM 5.1.1	Small effect on inundation. A more detailed DEM does provide a more realistic representation of the study area.	No effect on computation time.	Modifying the DEM to be suitable to use for D-HYDRO does take a couple of hours, however this only has to be done once. Also larger file sizes take longer to import in D-HYDRO.	Make a DEM map for the entire management area. When making a simulation, cut out a part of the DEM that is required for the simulation area. Make sure the file is not to big, because D-HYDRO is slower with larger files. The DEM resolution should preferably always be smaller than the grid resolution.
Flexible mesh 5.1.2 and 5.3	Using flexible mesh increases the level of detail in the simulation at the refined locations. This way the detail only increase in the desired area.	Adding refinements costs additional computation time, but this is more efficient than choosing a different grid size for the entire model. The user can choose where extra details are required.	Locations of the refinements need to be determined and added to the model. This takes additional time. With the current release of D-HYDRO, there are some bugs when using flexible mesh.	Use based on the requirements of the model. It does provide additional accuracy at the cost of computation time. The additional computation time can be used efficiently since the user can define the locations for additional calculations. It does cost quite some additional set up time, so it is only advised to use flexible mesh for simulations for simulations with a long computation time.
Courant number 5.1.3	In certain situations, the Courant number can be changed without changing the inundation.	Changing the Courant number has a significant impact on the computation time	No additional data or set up time is required.	It is recommended to use the 0.7 Courant number which is advised by Deltares. In certain situations, it can be beneficial to change the Courant number. But the user has to have a good understanding of the Courant

				number and its effects. It is generally not advised to use Courant numbers greater than 1.
Culverts 5.2.1	Including culverts has an effect on inundation, because they connect waterways that are not connected when using the regular DEM.	No effect on computation time.	The DEM has to be modified in order to include culverts. However, this can all be done beforehand. A DEM map including culverts should be made and added to the database.	It is advised to always include culverts within the DEM. Ideally, scale the size of the culverts to the same size as the waterways that the culverts connects. If this is not possible, make the culverts an appropriate size that ensures the culverts are represented on the DEM.
Roughness values based on land use 5.2.2	Adding roughness values based on land use has an effect on inundation. Adding roughness values provides a more realistic representation of the area.	No effect on computation time in general. However, in certain situations computation time can change because the water moves differently.	Roughness map has to be added to the model, which can be done quickly. Also, an additional map has to be made with the roughness values. This can be done beforehand and should be added to the database.	It is advised to use a representative roughness values of the land cover. It provides a more realistic representation of the real world. Also results can be influenced significantly with certain land uses like forests.
Precipitation 5.2.3	Does have an impact on the inundation. But small amounts of precipitation in comparison to the breach inflow do not make a significant difference.	Significant effect on computation time. Computation time can be much longer depending on model size. Computation time was 2x as long for the performed test.	Precipitation data has to be collected and implemented in the model; this takes some time.	It is generally advised not to use precipitation data because of the increase in computation time. However only when the amount of water from precipitation is significant compared to the amount of water from the dike breach it is advised to add precipitation data.
Wind 5.2.4	Has effect on inundation with high wind velocities.	No effect on computation time.	Wind data has to be collected and added to the model, this takes additional time.	It is advised to only add wind data when there is a lot of wind (more than 10m/s), and there is data available.
Dams 5.2.5	Significant impact on inundation. Especially if dam is not included in DEM or the grid size is bigger than the dam.	No effect on computation time.	Dams have to be added manually. In the current release of D-HYDRO, this is a lot of work since the crest height cannot be inserted automatically yet.	It is advised to add dams when the dams are not represented in the grid. For example: if the grid size is 50*50 meters, and the dam is 10 meter wide.
Angular grid 5.2.7	No significant impact on inundation.	No effect on computation time.	No effect on set up time.	The orientation of the grid does not matter. However, in certain situations, results could change slightly by having an angular grid.
Model size 5.2.8	No impact on inundation, as long as the model size is large enough to model the entire flood.	Significant effect on computation time. When the model is made larger than the flooded area, the computation time increase significantly.	No effect on set up time. With larger areas, more input data is required.	It is recommended to always have a model size that corresponds to the flooded area. To approximate the required model size, first make a large model with large grid cells, to get an approximation for the flooded area. Then adjust the model size accordingly. Or it can be estimated based on experience.
Initial water levels 5.2.9	Impact on inundation by having a more realistic representation of the real world.	Little to no effect on computation time. Can have a slight increase in computation time.	Map with initial water levels has to be added, this can be done quickly. Also, a map with the initial water level for the areas has to be made. This can be done beforehand based on target water levels.	It is advised to always use initial water levels. However, it should be noted that the water levels in case of a flood are not always the same as the target water levels.
Breach inflow 5.2.10	Can have a significant effect on inundation. A good estimation of the breach inflow is important.	Has a significant effect on computation time. More water in the system generally causes longer computation times.	Accurate data for the breach inflow is rarely available. Therefore, the breach inflow has to be estimated.	It is recommended for the user to have a good understanding of the different breach inflow methods in D-HYDRO. As for predicting the breach inflow, this is a process on its own. It is advised to work together with a specialist for this, since the impact on results can be significant.

7.2. Research question 3: How do D-HYDRO simulations compare to the earlier performed simulations in TYGRON?

Despite the uncertainty with regard to dike breach inflow, and the big difference in gird size cells, D-HYDRO and TYGRON simulations have shown relatively similar results. The comparison between TYGRON and D-HYDRO has also provided a benchmark to compare the performance of D-HYDRO models with different grid sizes. The D-HYDRO models with large grid cells have provided reliable results, within a short computation time. Comparing the different D-HYDRO models has shown that simulations with big grid cells provide reliable results, within a very short computation time. Using large grid cells does reduce the level of details of a simulation, however the overall inundated area is similar to smaller gird cells sizes. Also, the comparison has proven that flexible mesh grants additional accuracy with only a small increase in computation time.

The simulation of dike breach locations 3 and chapter 5.2.5 show the importance of adding an accurate representation of dikes to the simulation. With larger grid cells, this is an important factor that determines the accuracy of a simulation. With the current release of D-HYDRO, crest heights of dike need to be added manually. This is still a problem that needs to be fixed in order to make accurate simulations in D-HYDRO with larger grid cells.

Based on this research it is not possible to say whether D-HYDRO or TYGRON is preferred, because for this research, only the D-HYDRO software package has been used. From the information that is available about TYGRON, it is clear that D-HYDRO and TYGRON both provide different advantages. TYGRON ensures faster computation times. This allows the software to have smaller grid cells and model the entire management area at once with a small grid cell size. D-HYDRO has slower computation times when running on a laptop, but still provides good accuracy with bigger grid cells. It is also possible to run D-HYDRO simulations of computer clusters, which would speed up the computation time.

Furthermore D-HYDRO is more controllable since a simulation can be done on a single laptop. This is not possible in TYGRON since simulations have to be run on a supercomputer, this supercomputer is not always available. D-HYDRO also has many modules for different modelling purposes. This allows the waterboard to have many of the models all within the same software, which is a big advantage. As mentioned, it is not possible to say which software package is better for the waterboard based on this research. It can be concluded that D-HYDRO is a good software package that could fulfil the waterboards needs for flood modelling.

7.3. Main research question: How can the software suite D-HYDRO be used most effectively to model a dike breach fast and accurately, and thereby contribute to flood management for the waterboard?

Throughout the research, detailed advice has been given on how the software package can be used most effectively. To answer the main research question, the following summary points are advised:

- It is advised to make a rough (around 100*100 meter) model of the entire management area of the waterboard. Such a model can help to quickly model a dike breach, since the model is made beforehand. At the time of a risk of flooding, a dike breach location can be added, and the simulations can be run immediately. With this, within 10 minutes, a first estimate can be made. This 10 minutes includes set up and running time. The results of this model can be used to create more detailed models. This model should include the DEM, manually added dikes, and a roughness map.
- When making a model, the most important thing is to use an appropriate grid cell size depending on the goal of the simulation. Large grid cells up to 100 meters have been tested and provided fairly similar results as much smaller grid cells. Especially for simulations with large inundated areas. Do not hesitate to perform simulations with large grid cells, since they can provide good accuracy simulations within a short computation time. To determine the grid cell, look at the computation times of other performed

simulations. The computation time is influenced most by the model size, grid size, and dike breach inflow. These are the main factors that have to be considered when trying to estimate the simulation time.

- When using large grid cells, be sure to check for important dikes in the modelled area. When dikes are present that are smaller than the grid cell size, make sure to add these dikes manually to the simulation. However, in the current beta release of D-HYDRO this can be difficult since there is no way to automatically include crest height levels.
- Flexible mesh is a powerful tool that can be used. However, it does take additional time to set up. It is advised to only use flexible mesh for simulations with long computation times. With very short computation times, it is not worth the additional set up time.
- Use additional model input data according to the advice listed in Table 20. Keep in mind that when making rough simulations, it is not always worth the effort to include all additional input data.
- Have multiple people within the waterboard that can use D-HYDRO. In case of a flooding, there is a lot of uncertainty. When a flooding is expected it can help to have many simulations that simulate different scenarios. To run multiple simulations, it is helpful to have multiple employees simulate different dike breaches, to get a better insight on the risk of the situation. This should be possible since the software is easy to learn.
- For additional advice, read the additional advise in Appendix R: List of bugs/advise for D-HYDRO.

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9. Appendix

Appendix A: Model computation time

Running a model on multiple CPU's

D-FLOW FM offers the possibility to run a model on multiple CPU's. This aims to shorten computation times and run models that could not be run on a single computer. To do this, the mesh of a model is divided in different domains. Each of the domains has separate calculations, but at the boundaries, information is passed over to the other subdomains. This way, it functions like one model. This can be run both on computing clusters with distributed memory and shared memory machines with multiple processors and/or multiple CPU cores.

The speed up in relation to the amount of sub domains is tested by Deltares. The results can be seen in Figure 39. The blue line shows the speed up factor for different sub domains, the dotted line represents a linear relationship.

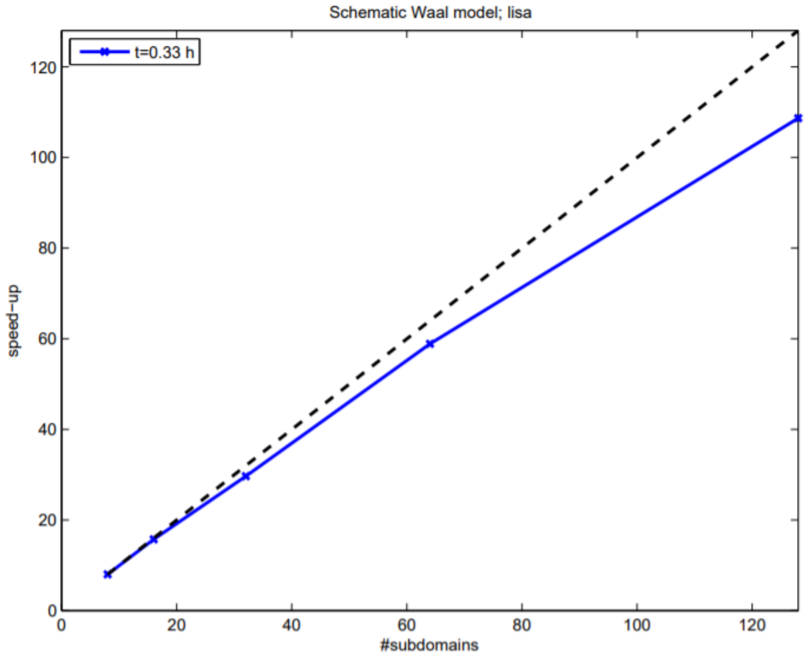


Figure 39: Speed up factor for different amount of sub domains (Deltares, 2019b).

The relationship is almost linear. This shows that partitioning and running the model on a cluster has a significant impact on computation time. Unfortunately, there is no high performance computing infrastructure at waterboard Noorderzijlvest.

Multi core parallelism

A more accessible alternative for speeding up calculations is using multi core parallelism. D-FLOW FM has built in support for this. It speeds up calculations by employing multiple processors in a single computer. This does not scale as well as MPI parallelism, but it does not require any changes in the model input. It can lead to double the calculation speed (on intel quadcore CPU). (Deltares, 2019a)

In order to run this on a laptop, the software openMP is required. At waterboard Noorderzijlvest, new applications need to be reviewed. Because of the limited time for this research, it is not possible to get access to the software. For this reason, multi core parallelism is not tested.

GPU calculations

D-FLOW FM does not provide the possibility to model floods on the GPU. TYGRON does use super computers with GPU's for 2D flood simulations (TYGRON, Dam break, 2020a).

Unfortunately, the calculation time for models in TYGRON for the study area near the Eemskanaal are not known. However, literature gives an insight on the possibilities with GPU computation for 2D flood modelling.

GPUs are attractive because they offer massive parallelism, high memory/data transfer between the motherboard and the GPU, and not just for graphics applications but also for non-graphics application (A. Kalyanapu, 2011). The speed up possibilities offered by GPU's can be seen in Table 21.

Table 21: Computation time for different hardware specifications.

System used for calculations	CPU	GPU (normal)	GPU 2 (high end)
Computation time (minutes)	545.9	146.1	6.2

Also, it is observed that the parallel processing power of GPU is more evident at higher spatial resolution with larger number of grid cells, which better incorporates complex topography and flow characteristics (A. Kalyanapu, 2011).

Appendix B: Input data

These maps are used from the database of waterboard Noorderzijlvest:

DEM (.tif files)

For the DEM, the maps AHN3 (5-meter) and AHN3 (0.5-meter) have been used.

Water bodies (shape files)

To determine where water bodies are within the area, the map “waterdeel” from Basisregistratie Grootschalige Topografie (BGT) has been used.

To determine characteristics of main water bodies, the map “aanvoertakken” has been used. This also is used to determine the location of main water ways, to determine location of grid refinement for flexible mesh.

Structures (shape files)

For general data about structures related to water, the map layer file “Kunstwerken” has been used. This layer file includes maps with data for culverts, weirs, dams, and other structures.

To determine where buildings are, the map “gebouwen” form BGT has been used.

Area characteristics (.tif and shape file)

For data about land use, “LGN 7” has been used.

For data about water levels, “Peilgebieden” has been used.

Appendix C: Grid size and DEM

Study area 1

Method 1: DEM with no data filled automatically. The results for different grid sizes excavated according to method 1 can be seen in Figure 40.

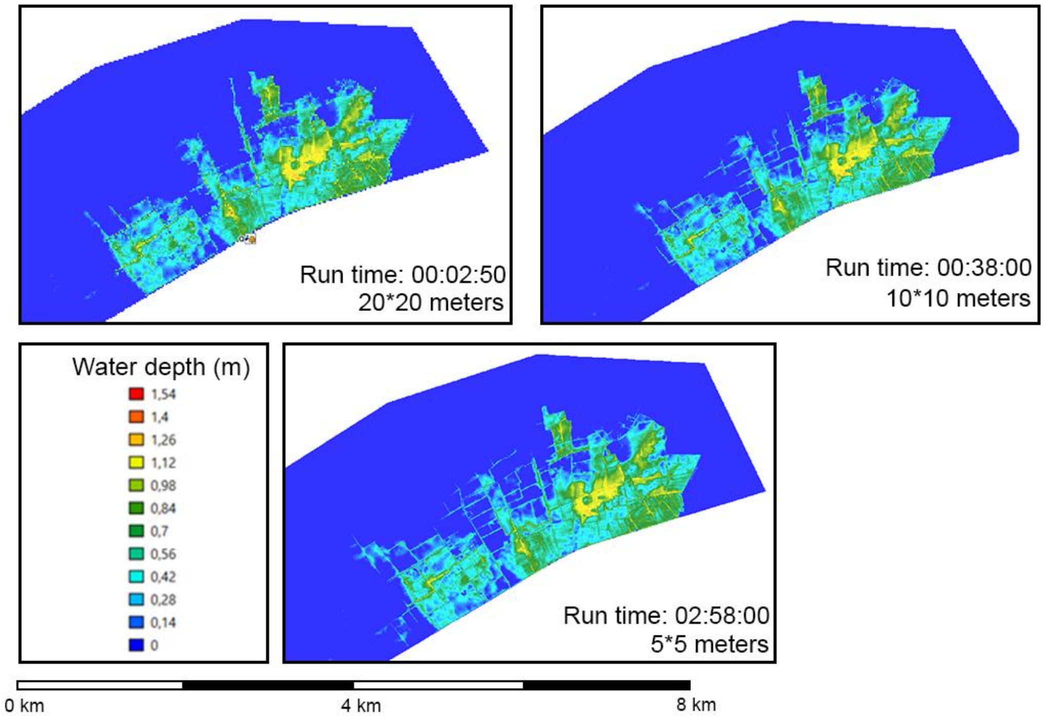


Figure 40: Results after 24 hours at different grid resolutions of 20, 10 and 5 meters.

The clearest difference between the 3 versions is that in the 5*5 model, waterways are represented more accurately. With larger grid cells, the small waterways get averaged out since there is not enough detail in the grid. With smaller grid cells, the waterways are represented better, and the water can travel through them. However, this does not have a big impact on the overall region that is flooded, this region is quite similar for the three models. The inundated area in the 5*5 model is slightly larger, because of the water ways that allow transportation to different areas.

Method 2: DEM with simple water ways and buildings. The results for different grid sizes excavated according to method 2 can be seen in Figure 41.

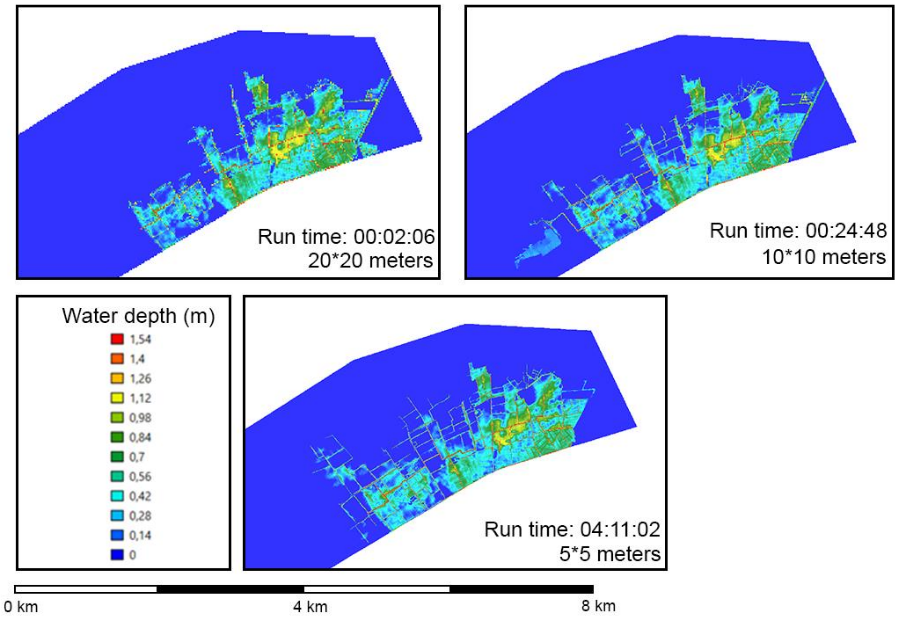


Figure 41: Results after 24 hours with excavation of 1.5 meters for all waterways for 20, 10 and 5 meter resolution.

As expected, the deeper waterways can take more water. This results in less inundated areas. With a smaller grid size, the waterways are better represented. This results in less water on land, and more in the waterways. This is also expected to happen in a real life flood. Excavating the grid has had a positive impact on the simulation.

However, it should be noted that currently waterways are represented bigger than some of them are. This is because of the resolution of 5m. This can cause a very small ditch, to function like a 5-meter wide waterway. This is not realistic.

Within this simulation, grid size is more important than in the previous test. With the coarser grids, the excavated water ways are being averaged out, resulting in more flooded areas.

Method 3: DEM with more complex water ways and buildings. A comparison for method 1, 2 and 3 for a grid size of 5*5 can be seen in Figure 42.

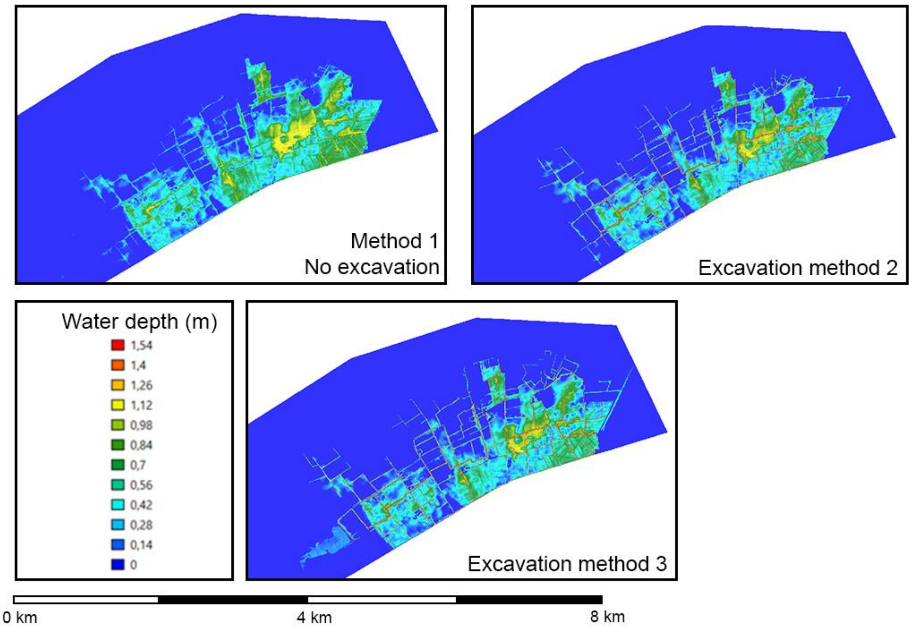


Figure 42: Results for different excavation methods after 24 hours at 5 meter resolution.

Methods 2 and 3 perform quite similar, but excavation method 3 resulted in more waterways containing water. It is hard to say if this is more realistic since there is no historical data to compare to. However, using basic reasoning, it is more realistic to assign different depth values based on the geometry of the waterway. The method used here might not be the most accurate, but it is a good estimation with the data that is available.

Comparing excavation methods 2 and 3 to no excavation, there are significant differences. These differences are mainly in water ways. However, even though there are differences, the overall flooded land area is quite similar. Also, the water depth within the flooded areas is similar.

General note: Within both of method 2 and method 3 DEMs, every water way is represented in the DEM, even though some might be a lot smaller than 5-meters (the resolution of the DEM). Because every water way essentially is being enlarged to 5-meters, they can hold more water than they would in real life. This mostly affects small ditches, and therefore, small waterways have been given a lower depth value than what they would have in real life. At the time of performing these tests, there was no access to the 0.5-meter DEM yet. Later, a more accurate DEM excavation has been made. This method is similar to excavation method 3, but with a higher resolution.

Study area 2

The models of study area 2 used the same 1 meter accurate DEM. This DEM has been excavated according to Appendix D: DEM excavation method 3. The results of the simulation can be seen in Figure 43.

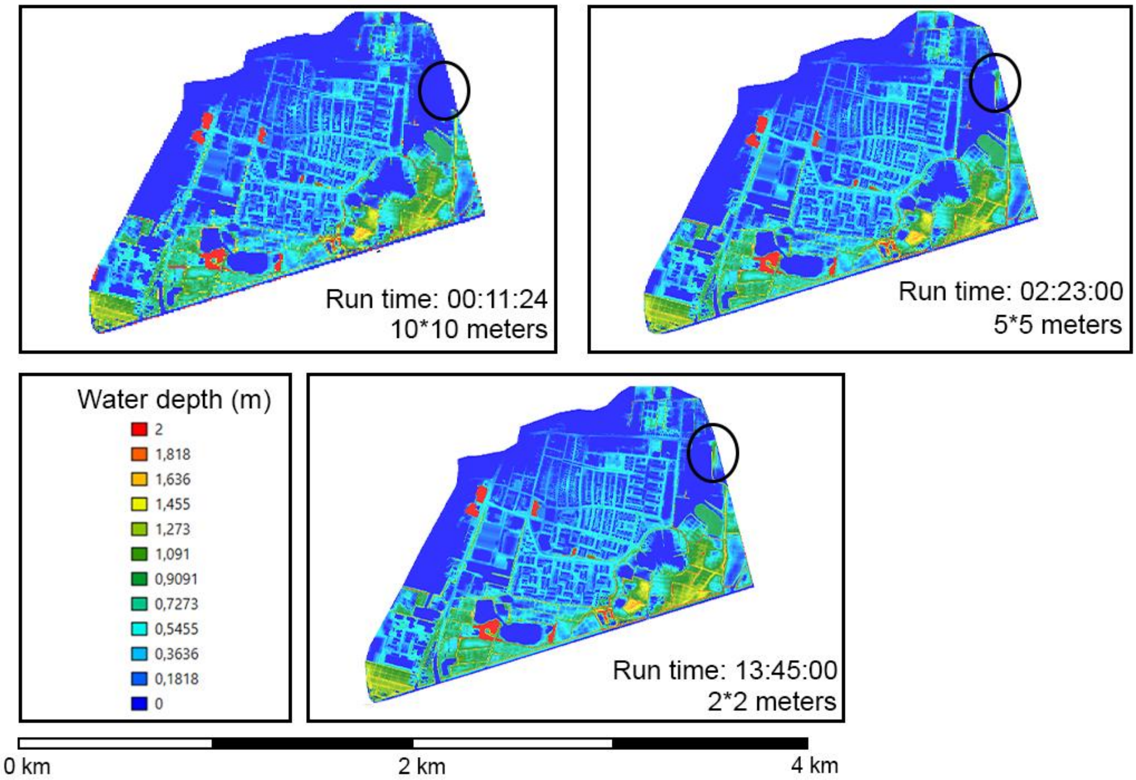


Figure 43: Results after 12 hours for study area 2 with grid sizes of 20, 10 and 5 meters.

Like in the previous tests, the higher resolution gives a better view of the details within the modelled area. However, these details have little effect on the overall area that is flooded. One area in the 10*10 is not flooded but is flooded in the others (marked with black circle). Apart from that, there are only differences in the details.

Appendix D: DEM excavation

DEM excavation method 1

The first method used to create the DEM, is by using the AHN3 5-meter accuracy map. The AHN3 map does not contain elevation data for water bodies and buildings. Places with water bodies or buildings are labelled with “no data” in the DEM. For this first method, the “no data” values are filled based on neighbouring cells. The 5-meter DEM is used.

DEM excavation method 2

No data values are first filled according to method 1. After this, water ways and buildings are included in the DEM by increasing or decreasing the elevation data. For this method, every waterbody has a depth of 1.5-meters, and every building has a height of 8 meters. The waterbodies and building locations are based on maps from the BGT.

Since the 5-meter DEM is used, every water way is enlarged to fit on this resolution. This can cause small ditches to have a width of 5-meters in the model.

DEM excavation method 3

This method is like method 2, but instead of every water way being 1.5-meters deep, the depth depends on the geometry of the water way.

In real life, on average, water ways that are wider are also deeper. For example: A lake is wider and deeper than a ditch. However there also is no data available on the width of the water ways. To address this, a method has been derived to approach this for large datasets:

Within the available maps, waterways are mapped as polygons, polygons have a perimeter and an area size. The relation between the perimeter and area generally tells something about the width of the polygon. A very narrow waterway has a bigger perimeter relative to its area. The location and size of waterbodies is based on maps from the BGT.

An example to show this method is viable, these are all waterways with a relation of area/perimeter>4. Indeed, only larger waterways are selected:

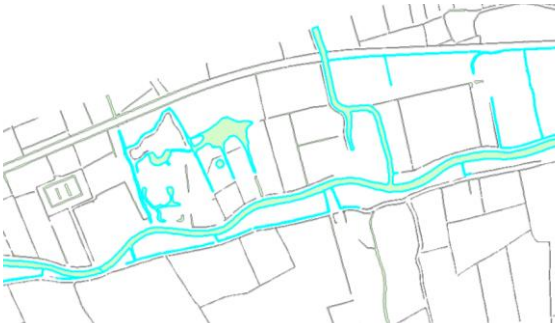


Figure 44: Example of selection based on the relation between area and perimeter.

Table 22: Depth allocation for waterways in excavation method 3.

Relation perimeter/area	**<0.5**	**0.5<1**	**1<2**	**2<5**	**5<8**	**<8**
Depth (m)	0.5 m	0.75 m	1 m	1.5 m	3 m	4 m

DEM excavation method 4

This method combines excavation method 3, with existing data about the depth of some of the main water ways. Also, the 0.5-meter DEM is used. If data is available on the depth of a water way, this data is used. Otherwise, depth is estimated by this table:

Table 23: Depth allocation for waterways in excavation method 4.

Relation perimeter/area	<0.5	0.5<1	1<2	2<5	5<8	<8
Depth (m)	0.5 m	0.75 m	1 m	2 m	3 m	4 m

The height for every building is 8 meters.

The resolution of the resulting DEM is 2-meters. It is limited to 2-meter (and not smaller) because D-HYDRO cannot handle larger .xyz files on my laptop. D-HYDRO interpolates the values. For example, if D-HYDRO has a 5-meter grid size, there are multiple data points of the 2m DEM within the grid size.

In contrast to the previous methods, waterways are not scaled up to fit the resolution. The 0.5m DEM is used (earlier it could not be downloaded, so it was not used). The water way data is directly excavated from the DEM.

Procedure excavating DEM according to method 4

The 4 data sources used to create this DEM are:

1. Map containing waterways (BGT) (polygon)
2. Map containing buildings (BGT) (polygon)
3. The DEM of the area (AHN3) (raster)
4. Map containing main water ways (aanvoertakken), this map also includes the depth for some water ways (lines).

First the "no data" value cells of the basic AHN3 are filled in based on their neighbouring cells. After that, in all the places where there is a water way, the DEM is lowered by the depth of the water ways. All the places where there is a building, the DEM is made higher by 8 meters. The resulting map is used in the model.

Steps to take:

- Collect DEM, water map and building map.
- Clip all data for desired area.
- Spatial join map containing main water ways and depth values, to regular map containing water ways. Now separate the water ways in 2 categories: with recorded depth values, and without recorded depth values.
- Fill DEM AHN3 no data values (QGIS) based on neighbouring cells.
- Add height data to the water and building map. Let depth of water depend on relation area/perimeter.
- Convert water (without recorded data) and building map to raster, also create an additional raster for the entire study area. Use the earlier mentioned height value as a raster value.
- Combine the three rasters to one raster.
- Add the resulting raster to the earlier made DEM.
- Add the elevation data of the water ways that had recorded data to this DEM.

Culvert excavation

To include culverts in the DEM, they have been excavated like a regular water way. On the location of a culvert, the DEM is lowered.

Option 1

Culverts are excavated based on their width. However, most culverts are too small to be represented on a 2-meter DEM. For this reason, if a culvert has a width smaller than 2-meters, the width is set to 2-meters. The excavation depth for the culvert is the culverts height + 1 meter. The average culvert is assumed to lay 1 meter under the surface. If no data for width or height is recorded, the width is set to 2 meters, and the height to 0.5 meters.

Option 2

All culverts are excavated with a width of 6 meters. The depth is determined in the same way as in option 1.

The features resulting from this are excavated from the raster that was constructed in method 4. This means every building has a height of 10-meters. Waterways with recorded depth data are included with the depth data. If no depth data is available, the depth is determined by the relation between area and perimeter according to Table 23.

Appendix E: DEM accuracy relative to grid size

In chapter 5.1.1, the effect of both the grid size, and the DEM have been tested. One of the problems that occurred during the DEM excavation, is that some ditches are smaller than the resolution of the grid size. This can be solved by having a smaller grid size, or by widening the ditches to represent them on the DEM.

In this test, 2 methods are compared. Method 1: widening the ditches to represent them on a 5-meter resolution map. Method 2: Using the regular ditches and represent them on a 0.5-meter resolution map. Export this map to a size of 2m DEM (otherwise file is too big for D-HYDRO). And then let D-HYDRO interpolate this map over the bigger grid.

With this test it can be seen whether it is worth the effort to create a more detailed DEM. This depends on how D-HYDRO uses this DEM in its grid interpolation. For the test we have a 10*10 model of study area 2. One model used method 1 and the other used method 2. The two are compared to the 2*2 meter model from chapter 5.1.1.

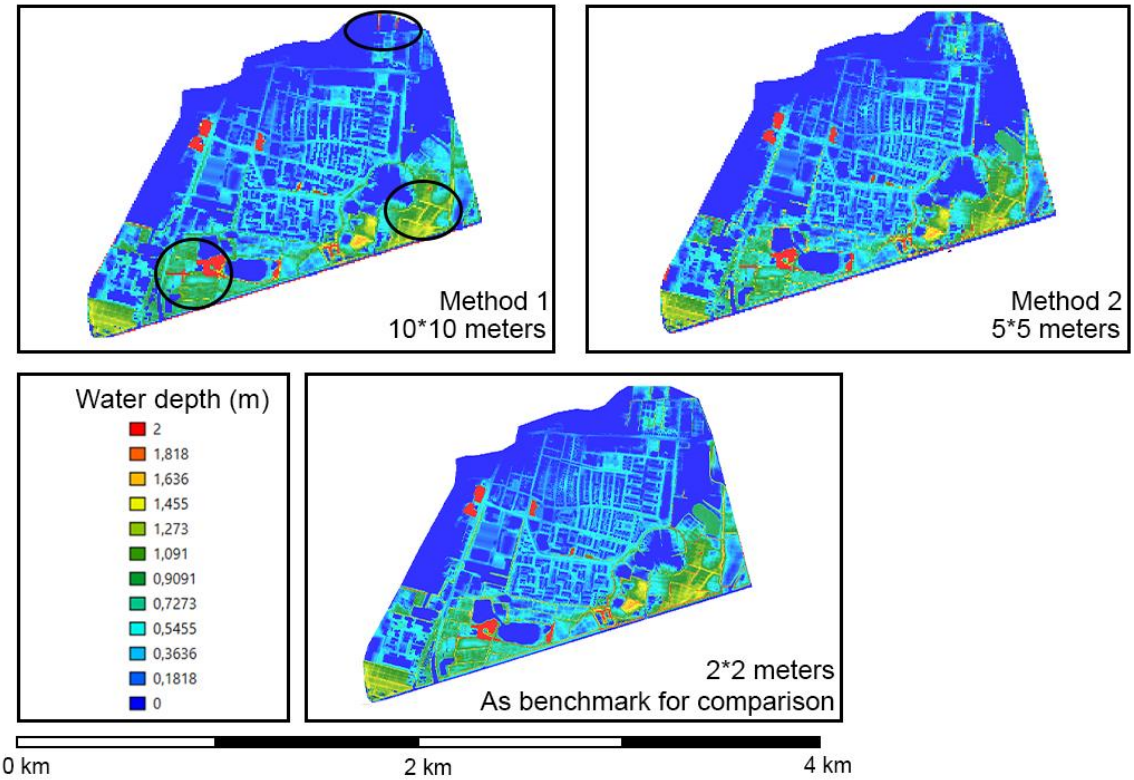


Figure 45: Results of test with different DEM's (top), and the 2*2 model (bottom) as a benchmark to compare the performance of method 1 and method 2.

Looking at the results in Figure 45, they are similar. However, there are some differences, highlighted by the black circle. Overall, method 2 is closer to the grid size of 2*2. But these differences are very minor. Computation time seems not to be affected by changing to a higher resolution DEM. It does increase the time it takes to interpolate the DEM on the grid.

An additional test has been done on a more detailed grid. The results can be seen in Figure 46.

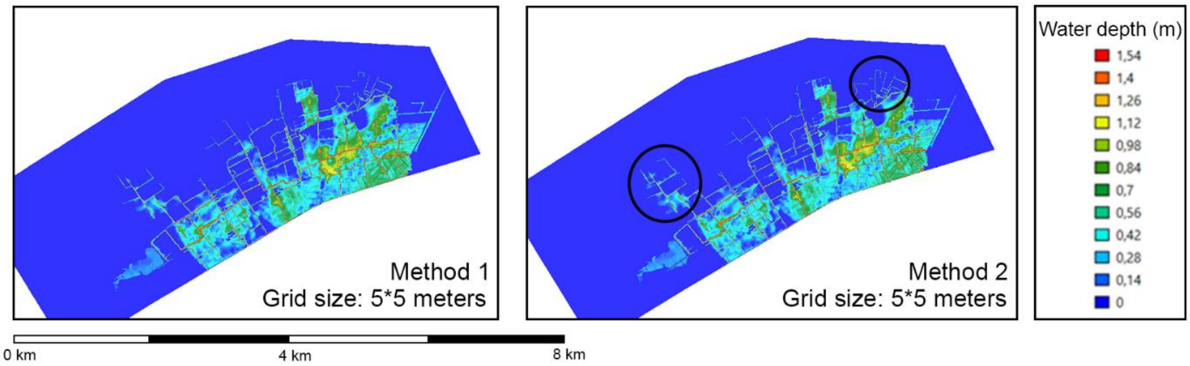


Figure 46: Results of tests for different DEM's on study area 1.

Again, the results are similar. There are some small differences, highlighted with a black circle. From the differences, it looks like method 2 provides slightly more detail, the inundation seems more realistic. However, this is just speculation, and cannot be validated with real data.

With method 2, water ways do not have to be widened to fit on the DEM. This is regarded to be more accurate. Therefore, when possible, a high resolution DEM is used, like in method 2. This DEM is interpolated over the grid cells in D-HYDRO. Appendix F: Interpolation explains more about the interpolation process.

Appendix F: Interpolation

D-HYDRO allows for different interpolation methods. Triangulation and averaging. Their performance is relatively similar for the models that are tested. Triangulation is used for all simulations in this study. In Figure 47 it can be seen how samples in a grid cell are interpolated to come to a height of the grid cell.

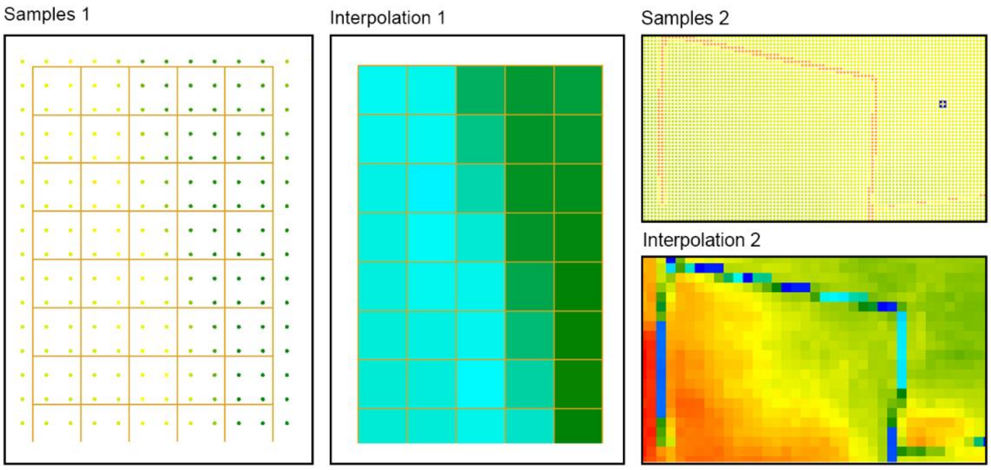


Figure 47: Interpolation of samples on to the grid.

If a DEM contains a ditch of 2-meters wide, and the grid is 5-meters wide, the ditch is not completely ignored. If the 5-meter grid cell contains 4 sample data points, with 2 of these data points being the ditch, these will be averaged out together with the other 2 sample points not containing the ditch. The result is that the height of that grid cell is an average of the ditch and the land.

Appendix G: Courant numbers

All the tests that are done on Courant numbers for study area 1, are represented in Table 24. From the tests it follows that a Courant number of 50 provides accurate results on all tests performed. By using a Courant number of 50, the computation time speeds up by about 4x. It was not expected that the output of the model would stay the same with a higher Courant number before performing these tests. That is why many validations have been done. All of them show that a Courant number of 50 is useable for the tested models.

Table 24: All tests on Courant number with their characteristics

			Run time (hh:mm:ss)			
Study area	**Grid size**	**DEM**	**Courant 0.7**	**Courant 50**	**Ratio run time**	**Results**
1	20*20	5*5 method 1	00:02:50	00:00:43	4.0	Identical, nearly perfect match
1	10*10	5*5 method 1	01:10:00	00:16:16	4.3	Identical, nearly perfect match
1	20*20	5*5 method 3	00:02:06	00:00:37	3.4	Identical, nearly perfect match
1	10*10	5*5 method 3	00:24:48	00:08:58	2.8	Identical, nearly perfect match
1	5*5	5*5 method 3	04:11:02	00:38:19	6.6	Almost identical
2	2*2	1*1 method 3	33:00:00*	14:00:00*	2.4	Almost identical

*Estimation because computer went to sleep within simulation.

Results for the inundation with different Courant numbers can be seen in Figure 48.

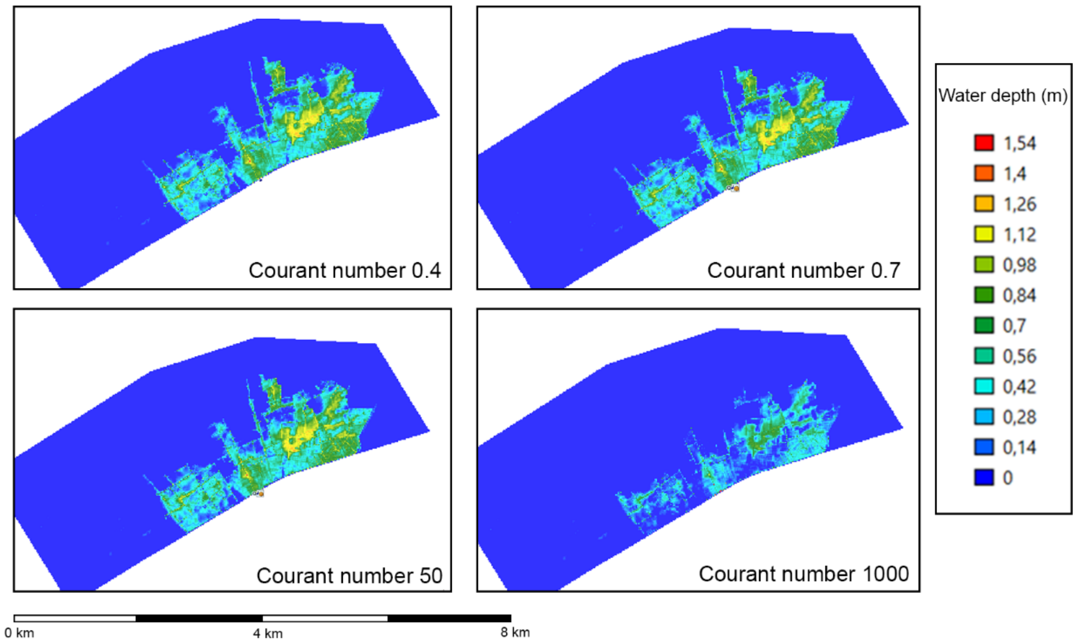


Figure 48: Results after 24 hours of a 20*20 model with different Courant numbers (only 0.4, 0.7, 50 and 1000 are shown).

From a Courant number of 0.4 to a Courant number of 50, the results are nearly identical for each model that has been tested. For the Courant of 1000 and 10000, the model results started to differ from the lower Courant numbers. For the specific model used in this comparison, a grid size of 20*20 meters, and an inflow of 25m^3/s, a Courant number of 50 is the best choice for optimal computation time while maintaining accuracy.

To see how a Courant number of 50 works for different models, 2 versions of a 10*10 and 5*5 model have been run. One with Courant number 0.7 and one with Courant number 50. The results can be seen in Figure 49.

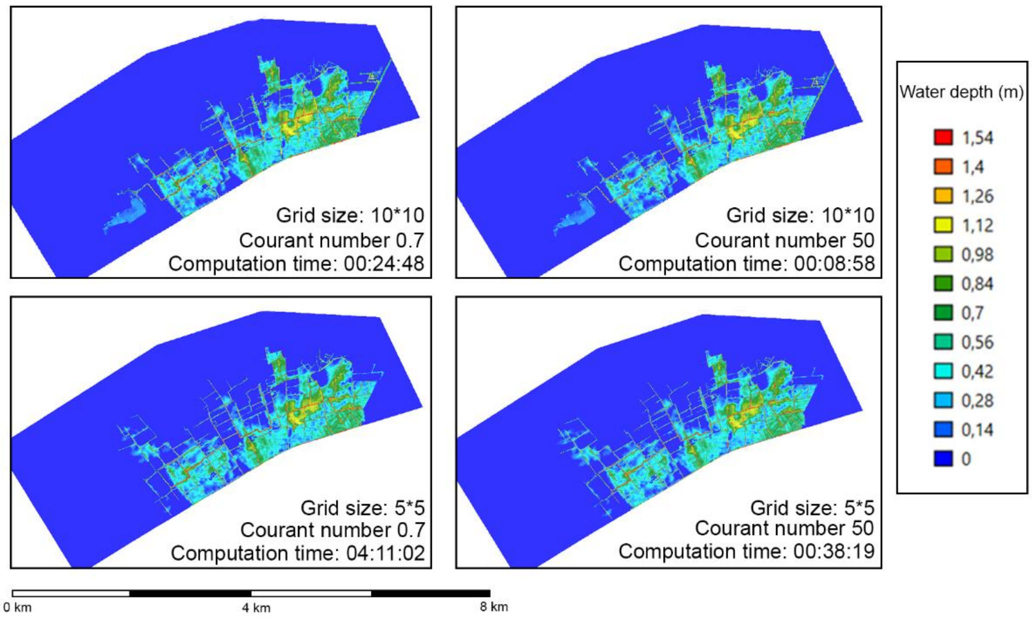


Figure 49: Comparison of output for study area 1 with Courant number of 0.7 (left), and with Courant number of 50 (right).

For the 10*10, there is almost no visual difference between the two. However, the model with Courant number 50 is almost 4 times faster. This further indicates that using a higher Courant number could be beneficial. For the 5*5, there are some minor differences. However, these are small details. This again shows that a Courant number of 50 is useable for flood simulations of this size.

With the help of some additional research, a hypothesis is made for why a Courant number > 0.7 still provides reliable results.

Each time step, the new time step is determined based on the Courant condition. This is done according to equation 10 (Deltares, 2020a).

$$C = \max\left(\frac{u_x \Delta t}{\Delta x} + \frac{u_y \Delta t}{\Delta y}\right) \tag{10}$$

D-HYDRO calculates the maximum Courant number on the computational grid, and it adjusts the time step accordingly. Within the simulations that have been performed on a fixed mesh, the grid size or delta x and delta y remains unchanged. The only variable is the covered distance of the water within the previous timestep.

The covered distance depends on the velocity, and the current time step. The current time step is equal for every location in the model. So, the Courant number is determined by the cell where the water velocity is the largest.

The locations with the highest velocities, have significantly higher velocities than the rest of the grid. Think of certain points where the water has to squeeze through a small area. The time step is adjusted for the few cells with the highest velocity. However, the rest of the model would also suit a smaller time step since the water flows a lot slower there. If a higher Courant number is allowed, all the slow flowing cells still have a Courant number lower than 1. Only the cells with the highest velocities have a Courant number near the maximum allowed Courant number.

This means, by taking a higher maximum allowed Courant number, it would only affect the few cells near with very high velocities compared to the rest. The other cells have a lower Courant number. Inaccuracies due to a big time step near the breach will later be evened out by the rest of the grid.

To test this hypothesis, the velocities at the breach location are changed, to see if it changes the computation time. To this, multiple models have been created. These models are all the same, with the only variable being the breach width. **The breach has the same inflow of 25 m^3/s**, but over a varying width. With smaller widths, higher velocities are expected. If the hypothesis is right, the time step is adjusted according to the highest velocity. Higher velocities should lead to smaller time steps, and thus longer computation time.

Table 25: Computation time for models with different breach width. Breach width is expected to affect flow velocity and thus computation time.

Breach width (meters)	Computation time (hh:mm:ss)
150	00:02:49
50	00:02:57
35	00:04:50
20	00:08:13

So indeed, with smaller breach widths, the computation time increases. The velocities are shown in Figure 50.

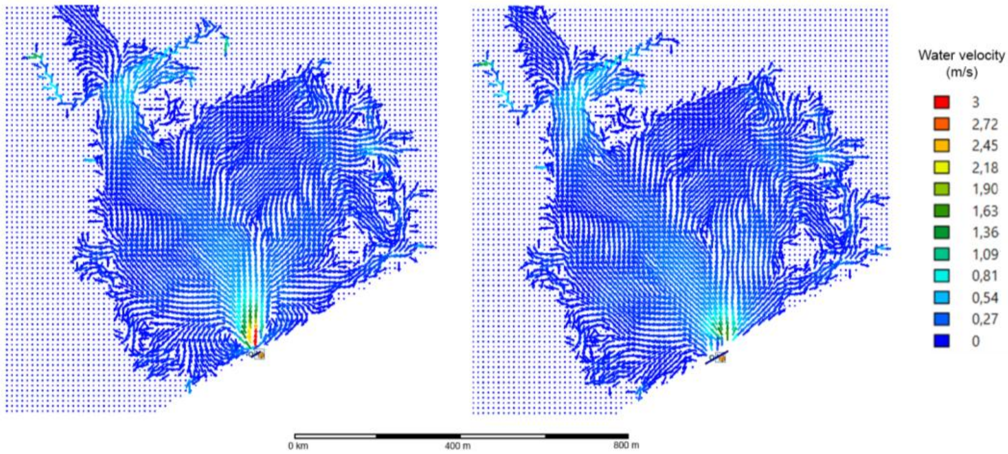


Figure 50: flow velocities in m/s for breach width 20-meters (left) and 50 meters (right)

The model can also output the number of times a cell was Courant limiting. This output can be seen in Table 26.

Table 26: For different breach widths, the number of times the cell next to the breach was the limiting factor for determining the Courant number.

Breach width	How many times highest velocity cell next to breach is Courant limiting
20-meters	5994
35-meters	5384
50 meters	976
150 meters	27

And indeed, with smaller breach widths, the Courant number gets limited by the cells near the dike breach more often. At both 20 and 35-meters, almost always the Courant number gets determined by the cells near the dike breach. This means that with these dike breach sizes, the velocity at the dike breach is higher than any other velocity in the field.

The reason that there is barely any difference between the computation time in 50- and 150-meter breach sizes, is because at this point, the velocity near the breach is not as high anymore. Because of this, the velocity is quite similar to the rest of the model. And thus, not affected by the breach size as much as before.

With this test, the hypothesis is assumed to be correct. The Courant number of 50 has been usable and did not affect the output, because the Courant number is determined at the highest velocity point in the field. Most of the field however, has a significantly smaller velocity. By increasing the maximum Courant number in the field, most of the cells still have a Courant number <1. Because the velocity at most locations, is significantly lower than at the highest location in the field. For this reason, the inaccuracy that might be created in cells with Courant number > 1, is negligible compared to the other cells. This of course depends on the Courant number chosen.

Appendix H: Roughness values

To have roughness values that are based on the land use, literature has been used to estimate the roughness for different land use (Papaioannou, et al., 2018). The LGN7 map has been used to assign roughness values to the right locations. The resulting roughness map from LGN7 is quite coarse, it has 25 meter grid cells. These grid cells are interpolated on the grid in D-HYDRO. The Manning roughness coefficient per land use type can be seen in Table 27. In Figure 51 the roughness values in study area 1 and 2 can be seen.

Table 27: Assigned Manning roughness coefficient to land use.

Land use according to LGN7	Assigned Manning roughness coefficient	Land use according to LGN7	Assigned Manning roughness coefficient
Agricultural grass	0.035	Bare ground in primary build territory	0.04
Corn	0.04	Main roads and railways	0.013
Potatoes	0.04	Buildings in rural area	0.013
Beets	0.04	Grass in secondary build territory	0.04
Cereals	0.04	Salt marshes	0.05
Other crops	0.04	Sand	0.025
Greenhouses	0.013	Heather	0.05
Orchards	0.1	Heather with some grass	0.05
Flower bulbs	0.04	Heather with much grass	0.05
Deciduous forest	0.1	High bog	0.05
Coniferous water	0.1	Forest in high bog	0.1
Fresh water	0.05	Other swam vegetation	0.05
Sea water	0.07	Reed vegetation	0.05
Buildings in primary build territory	0.013	Forest in swamp	0.1
Buildings in secondary build territory	0.013	Nature grasslands	0.04
Forest in primary build territory	0.1	Tree nurseries	0.08
Forest in secondary build territory	0.1	Fruit farms	0.08
Grass in primary build territory	0.04		

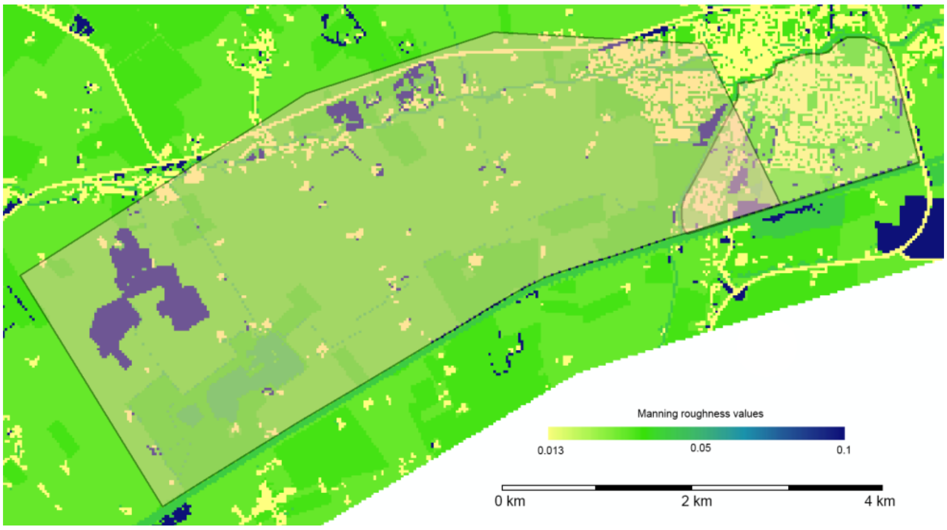


Figure 51: Manning roughness values in study area 1 and 2.

Also, additional tests on coarser grids have been done, to see if roughness has a different effect on a different resolution. The results can be seen in Figure 52.

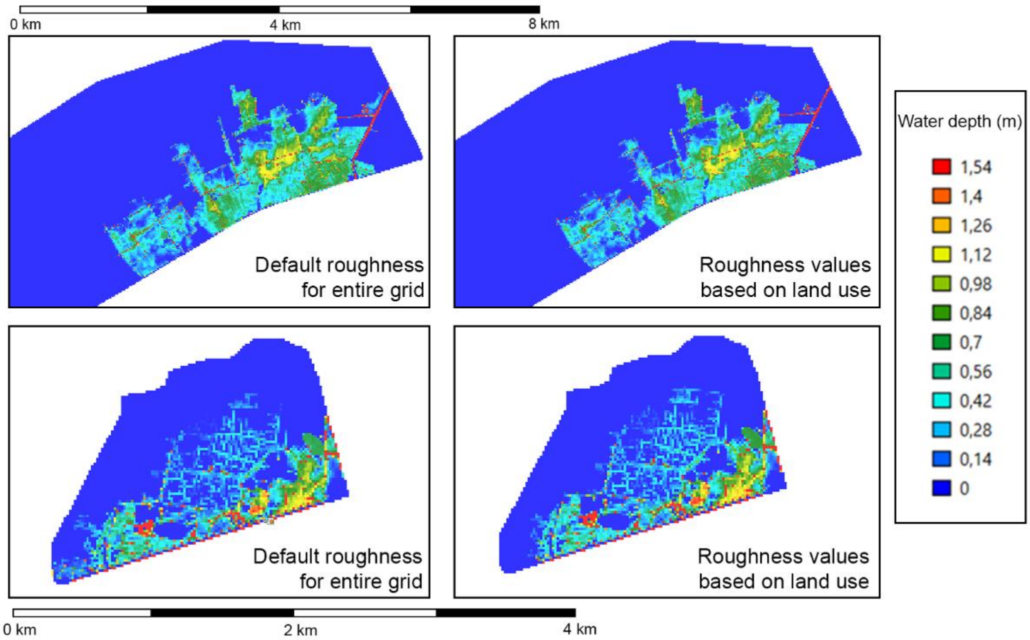


Figure 52: Results with default roughness value of 0.023 (left), and with roughness values based on land use (right) at a grid resolution of 20 meters for both study area 1 and study area 2.

Again, the differences are quite small in area 1. Area 2 does provide more differences in the inundated area. It is hard to say if adding roughness values makes the model more accurate.

Appendix I: Wind

In chapter 5.2.4, the effect of wind on the model has been tested. Based on the results of these tests, additional tests have been done to get a more detailed look at the effect of different wind speeds and directions. These tests have been performed on a 20-meter grid. This grid size has been chosen because of the low computation time. These results should not be compared to the results in chapter 5.2.4 because of the difference in grid size.

2 wind speeds have been tested, 10 m/s and 20 m/s. This corresponds to a 5 and 8 on the scale of Beaufort. 5 is described as moderately powerful wind: Blowing dust annoying the eyes, waves on lakes and channels, trash bins fall over due to wind. 8 is described as stormy: moving is difficult due to wind (KNMI, 2020b).

For the test, 4 different wind directions are considered: North-West, North-East, South-East and South-West. A North-East wind means the wind is coming from the North-East, going to the South-West. The results can be seen in Figure 53.

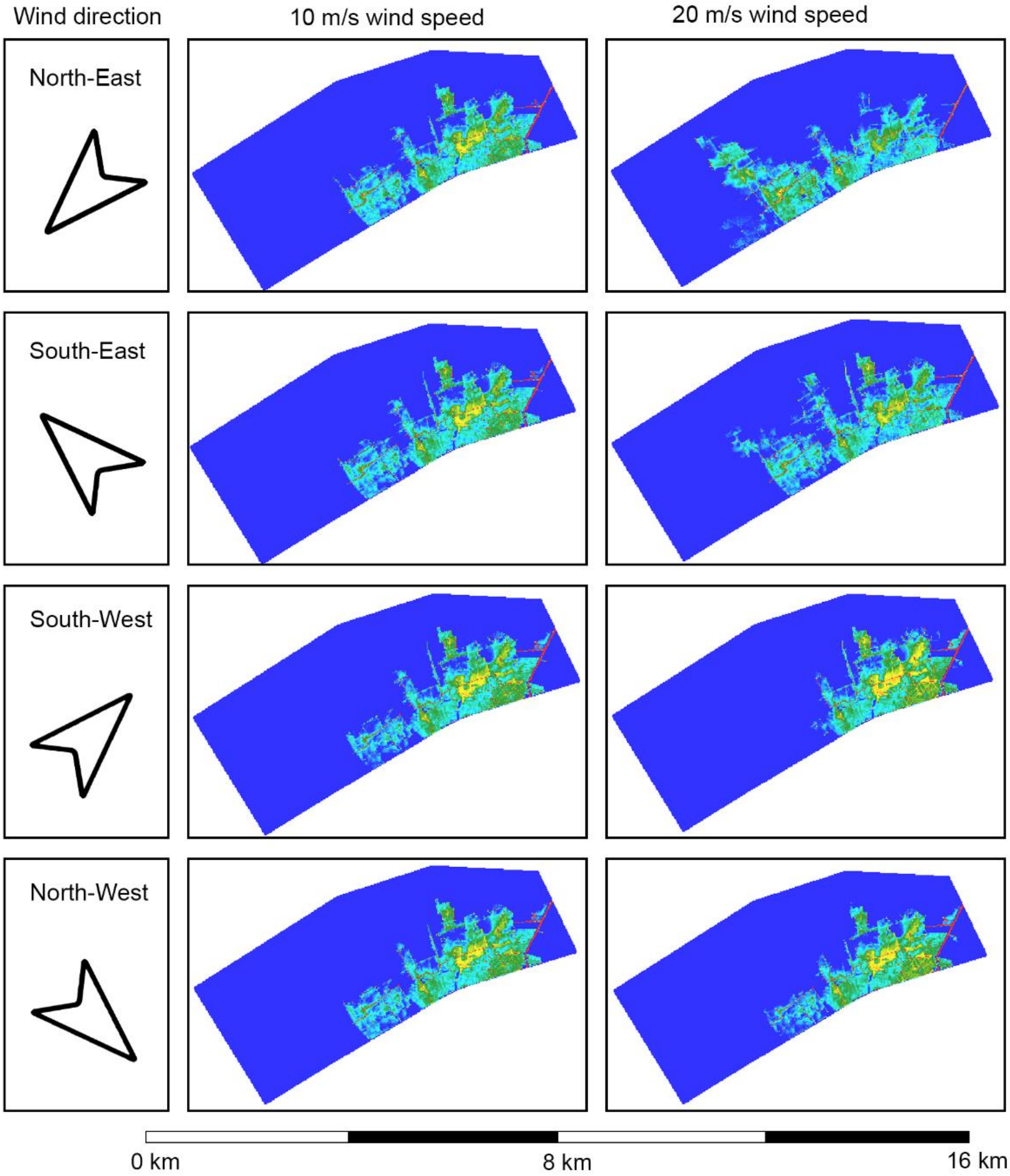


Figure 53: Results after 24 hours at different wind speeds and wind directions at a 20*20 model of study area 1.

From the results it is clear to see the wind direction and speed can significantly affect the results. At the lower wind speed of 10 m/s, the effect of wind is noticeable, but small. Roughly, the same areas are inundated, but the water levels do change with different wind directions.

With a wind speed of 20 m/s, which is high, the effects are significant. Based on the direction of the wind, completely different areas are inundated. This is an interesting result, and shows that wind speed, especially at higher speeds, is an important factor.

Appendix J: Precipitation

Based on the test performed in chapter 5.2.3, additional tests on precipitation have been performed. These tests are performed on a 20-meter grid resolution, and thus should not be compared to the results of chapter 5.2.3.

For this test, different precipitation intensities have been tested. The values that are tested are: 15, 25, 35, 45, 60, 80 and 100 mm per day. These values are based on data from the KNMI (KNMI, 2020a).

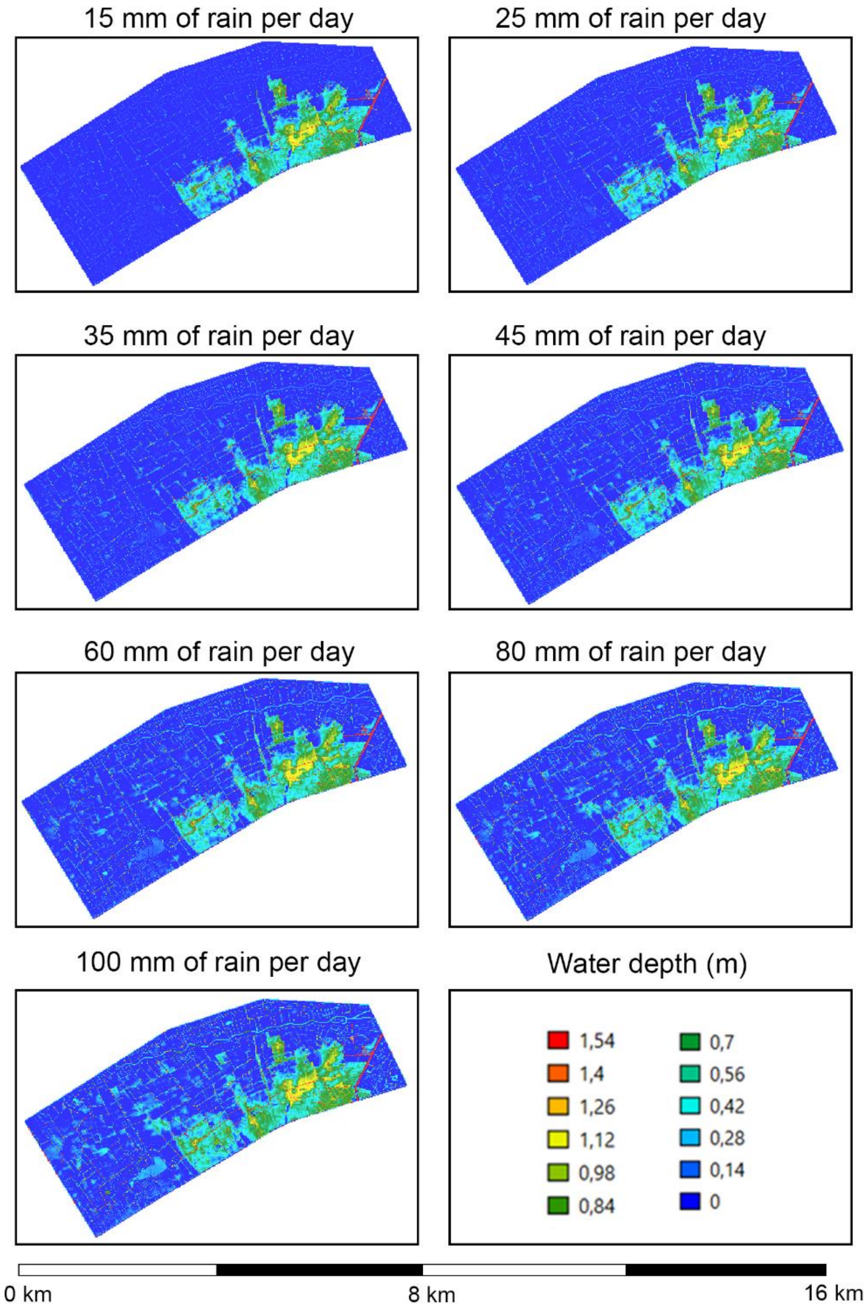


Figure 54: Results after 24 hours at different precipitation values for a 20*20 model of study area 1.

From the resulting inundation patterns in Figure 54, it is clear to see that adding additional precipitation has a significant influence on the results. No initial water level is present in the model, so with small amount of rain the effect is additional water in all waterways. Ideally the test would have an initial water level, but at the time of testing, initial water levels were not functioning in D-HYDRO yet.

With more precipitation, more water fills up the waterways. The inundated area due to the flooding does not change by a lot, but from a precipitation of 60 mm per day, there are visual differences. The reason that the inundated area due to the dike breach barely changes is simple: the amount of precipitation water is small compared to the dike breach inflow.

Maybe it would be interesting to see an option in D-HYDRO to only let rain fall on inundated area, this would not increase computation time as much, and still show a part of the effect of rain.

Appendix K: Model size

The different model areas can be seen in Figure 55.

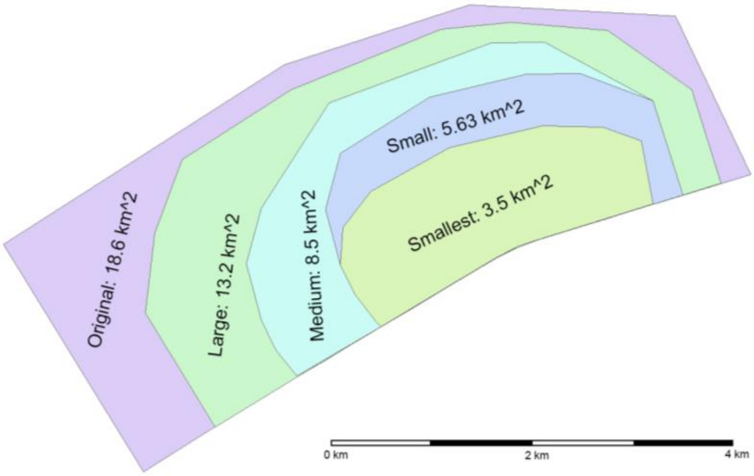


Figure 55: Differently sized modelling areas of study area 1 to test the influence of model size on computation time.

Appendix L: Initial water levels

The same tests performed in chapter 5.2.9 for different initial water levels on study area 1, are also done for study area 2. The results can be seen in Figure 56. The results are similar with and without culverts. Only results with culverts are shown.

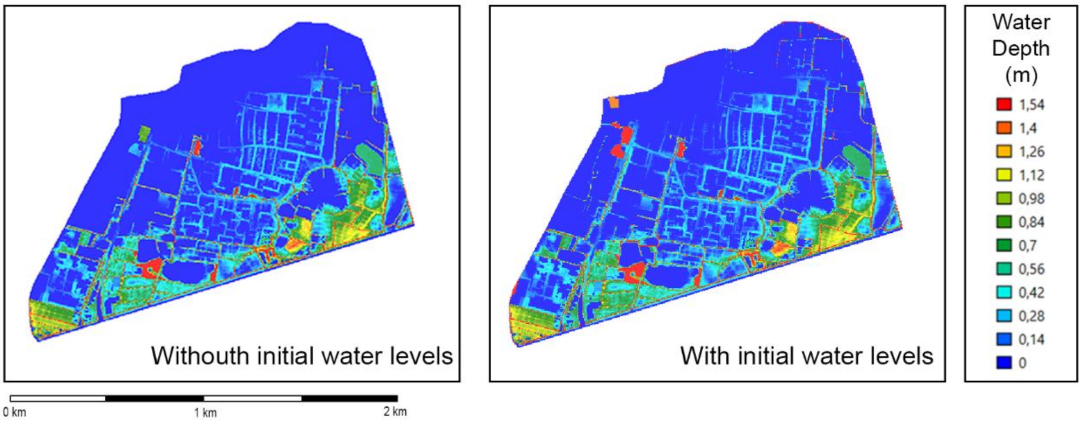


Figure 56: Results after 12 hours for study area 2 without initial water levels (left), and with initial water levels (right).

Overall, the inundation patterns are quite similar, with the exception of some details. Study area 1 has more differences caused by adding initial water levels. This is probably because in study area 1, there are more waterways.

Appendix M: Breach inflow

This appendix contains the full explanation about the 3 different methods have been tested to simulate a dike breach and the inflow. Method 1 and method 2 both use the boundary inflow option from D-HYDRO. Method 3 is modelling the Eemskanaal and connecting it to the grid of the inundated area via a dike breach.

1. Fixed inflow

This is the method that is currently used throughout the sensitivity analysis. Based on the location, size and inflow of a dike breach, D-HYDRO determines where water is added in the system. The amount of water is specified by the user. The advantage of this method is that the user can have a clear environment and it is known how much water enters the system. That is also the reason why this method is used throughout the sensitivity analysis, it provides a consistent output for comparisons.

The disadvantage of this method is that it is somewhat unrealistic. In real life, the inflow depends on the water level, bed level and breach size. These variables can change over time. By using a fixed inflow, these 3 variables are estimated in order to estimate an inflow. As the water in the inundated area rises, D-HYDRO keeps forcing additional inflow in the model. Inflow can be predicted ahead of time; however, this takes additional time.

Different values for the discharge have been tested, to see the effect on both computation time and model output. The tests have been performed on a 20*20 model of study area 1.

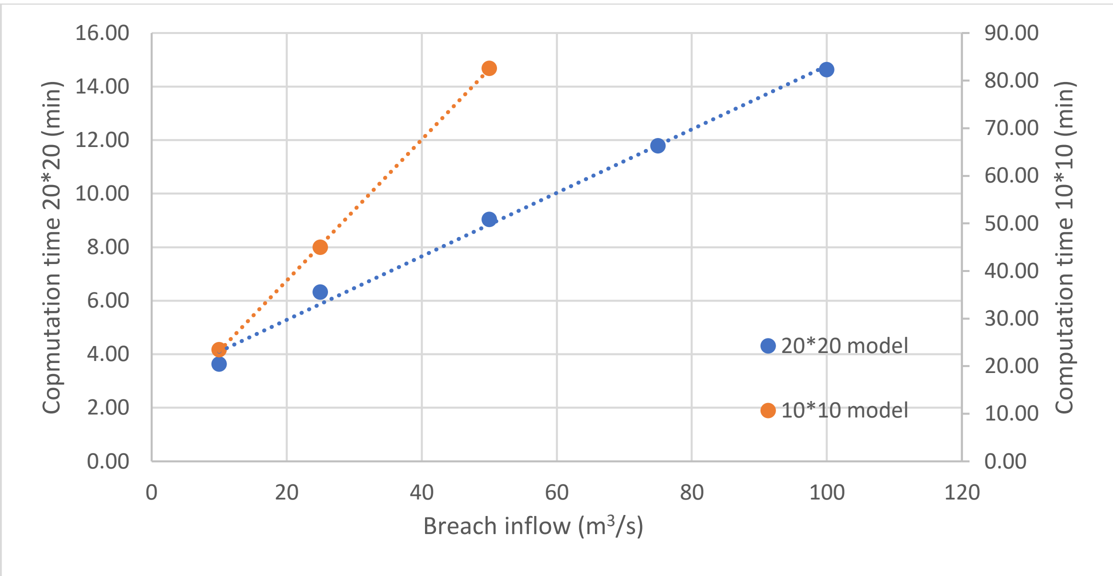


Figure 57: Plotted computation time for different breach inflows for study area 1, at both 20*20 (left axis), and 10*10 (right axis).

Table 28: Computation times for different breach inflows for study area 1 at both 20*20 and 10*10 meter resolution.

Model	Breach inflow (m^3/s)	Computation time (hh:mm:ss)
20*20	10	00:03:38
	25	00:06:19
	50	00:09:02
	75	00:11:47
	100	00:14:38
10*10	10	00:23:26
	25	00:44:57
	50	01:22:35

From Figure 57 and Table 28 it can be seen there is a clear correlation to breach inflow and computation time. The increase in computation time is a combination of 2 factors. Firstly, greater inflow results in higher velocities, which results in a smaller time step and thus longer computation time. Secondly, with greater inflow more cells are inundated, and thus more calculations have to be performed.

The results for the inundation patterns for different breach inflow can be seen in Figure 58.

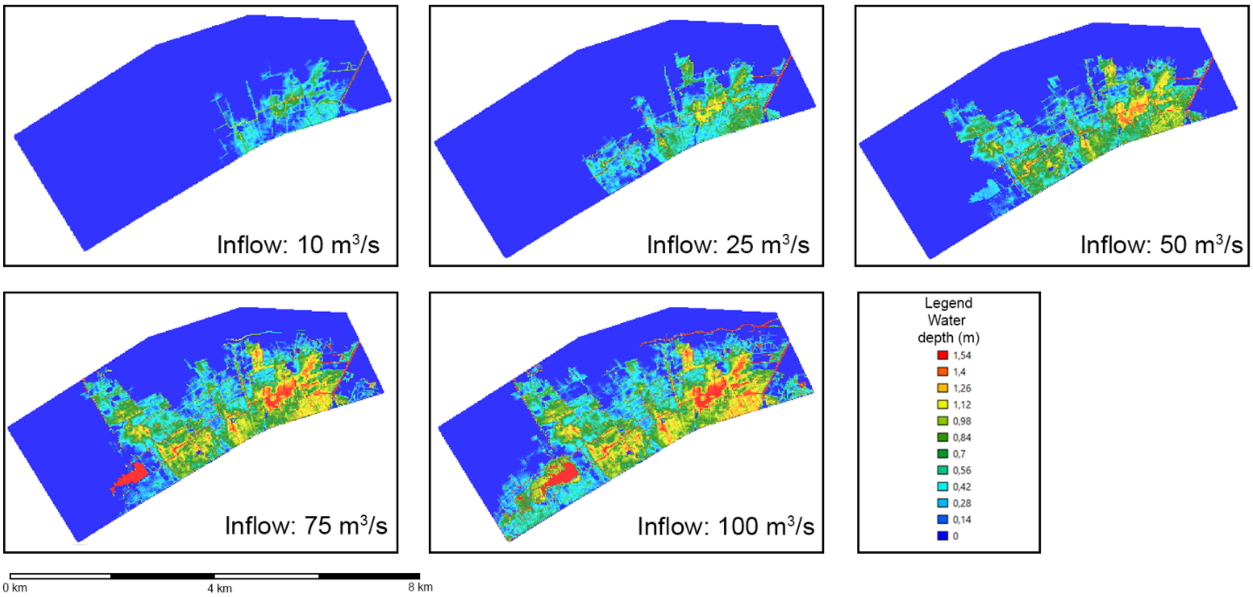


Figure 58: Results after 24 hours for study area 1 with different breach inflows of a 20*20 model.

Clearly, with a greater inflow, the inundated area significantly increases. This is logical, as the amount of water linearly increases with the inflow.

2. Specified water level

The second method specifies the water level of a dike breach at a certain location and with a certain size. From these characteristics, and with the bed level, D-HYDRO determines how much water flows through the dike breach. This is more realistic and dynamic than a fixed inflow.

Currently there is no method to make the water level depend on the amount of water that has flown from the source (Eemskanaal) to the rest of the model. Water level can be varied over time, but the user has to determine the water level before the start of the simulation. This is no problem in case the inflow is small compared to the volume of the source. However, in the case of the Eemskanaal, the water level lowers quite quickly due to the inflow. This change in water level is not taken into account by D-HYDRO and is difficult to predict before starting a simulation. This is a big disadvantage, and a feature that should be added to D-HYDRO.

Another important note is that the breach size can only be a multiple of the grid size. A breach inflow boundary condition with width 2 meters on a 20 meter grid, scales up to 20 meters.

For this method, different water levels have been tested, to see how the initial water level in the Eemskanaal affects both results and computation times. The discharge of the dike breach at different water levels has been measured as well, to get an idea for how the water level in the Eemskanaal affects the dike breach discharge.

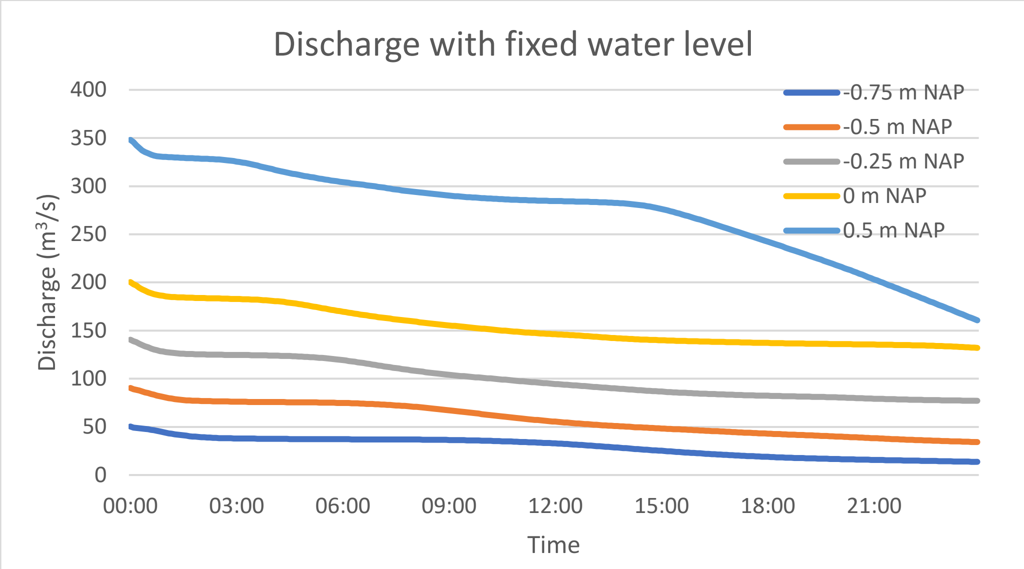


Figure 59: Discharge trough dike breach for study area 1 with different water levels of the Eemskanaal. The Eemskanaal is not modelled, but a dike breach of 20 meters with a fixed water level is specified. Bed level next to dike breach location is -1.88 meters.

From Figure 59 it is clear that the water level and the discharge through the dike breach are strongly correlated. With higher water levels, there are higher discharges. This is logical, since with higher water levels the difference between the water level and the bed level is larger.

Furthermore, it can be seen that over time, the discharge lowers. This also has a logical explanation: as time progresses, the water level in the inundated area increases. With this, the difference between the water level in the Eemskanaal and the water level in the inundated area gets smaller. Therefore, the discharge lowers. This does not happen at a constant rate since the bed level varies over space.

Also, for higher water levels in the Eemskanaal, the discharge decreases more rapidly. That is because with higher discharges, the water level in the inundated area increases faster.

Table 29: Computation times for different initial water levels in the Eemskanaal

Initial water level (meters from NAP)	Computation time (hh:mm:ss)
-0.75	00:03:17
-0.5	00:08:12
-0.25	00:10:24
0	00:15:14
0.5	00:25:18

In Table 29, there is a clear relationship between water level and computation time. This is logical, since the discharge is larger with a higher water level. This results in more water in the system, and thus more calculations. The results after 24 hours can be seen in Figure 60.

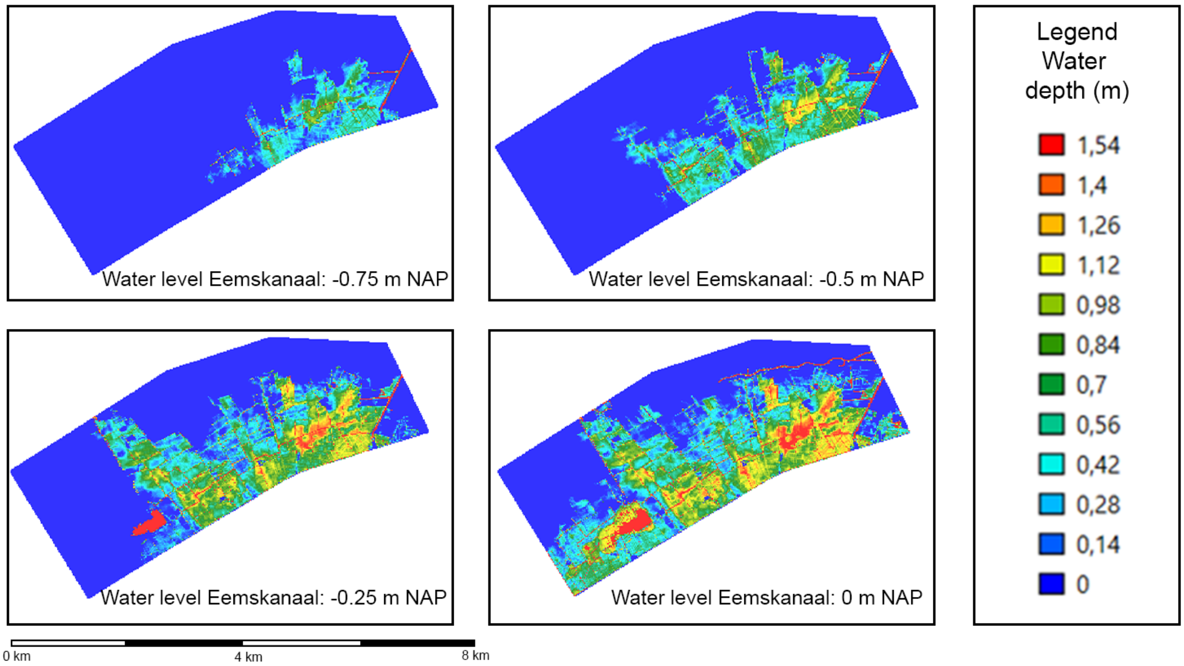


Figure 60: Results after 24 hours for study area 1 with different water levels in the Eemskanaal. Model resolution is 20*20 and breach width is 20 meters.

From the results in Figure 60, it is clear how much impact the water level in the Eemskanaal has on the inundated area. However, these figures are not an accurate representation of the real world. The water level in the Eemskanaal stays the same during all times, which is not realistic.

3. Modelling the water inflow channel

The last method is modelling the Eemskanaal within the D-FLOW FM model, and connecting it to the grid. This provides the most realistic results, as the water flow from the Eemskanaal to the flood area is taken into account in the model. However, it is hard to set up compared to the previous methods. Also, the dike breach size and location are not as customisable since the dike breach has to be a grid connection. It is tricky to create a grid connection between the Eemskanaal and the study area, and a careful approach is required to have a similar outcome each time. Also, D-HYDRO is unstable while working with multiple grids (in this case a separate grid for the Eemskanaal and the flood area), 10*10, and 5*5 models both crashed at various stages. Therefore only 20*20 models are tested for this method.

Various water levels for the Eemskanaal have been tested. All tests involve a 20 meter breach (smaller breaches required smaller grid cells, D-HYDRO crashes while trying to make these models with smaller grid sizes). In Figure 61, the water level over time in the Eemskanaal can be seen. In Figure 62, the discharge through the dike breach can be seen.

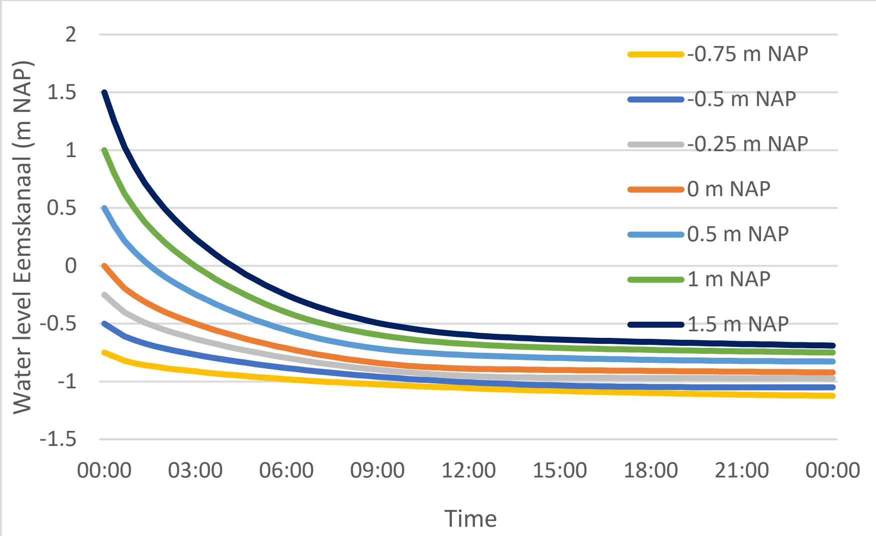


Figure 61: Water level in the Eemskanaal over time for study area 1, for different starting water levels.

In Figure 61, it can be seen that the water level in the Eemskanaal rapidly decreases. After 12 hours, a situation with a stable water level is present in all simulations. The stable water levels vary depending on the initial water level. This is because with higher initial water levels, a higher water level emerges in the flooded area.

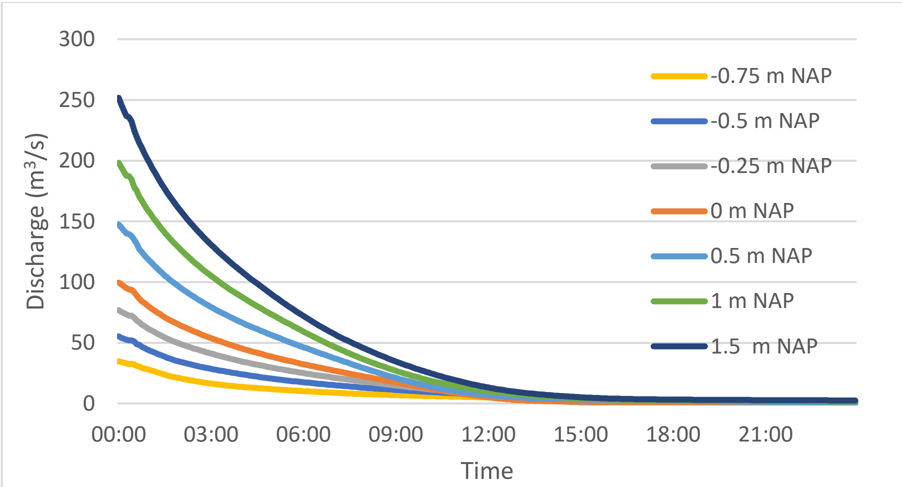


Figure 62: Discharge through the dike breach over time for study area 1, for different starting water levels in the Eemskanaal.

In Figure 62, it can be seen that discharge has a strong relation to initial water level, which is logical and explained in [2. Specified water level]. Also, the discharge rapidly decreases to 0. When the discharge is 0, the water level in the Eemskanaal is equal to that in the inundated area. This does not mean the simulation is finished. Water can still flow through the inundated area.

Table 30: Computation time for different starting water levels in the Eemskanaal for study area 1.

Initial water level Eemskanaal (meters from NAP)	Computation time (hh:mm:ss)
-0.75	00:03:40
-0.5	00:03:38
-0.25	00:03:38
0	00:05:37
0.5	00:08:59
1	00:11:53
1.5	00:11:02

Table 30 shows that there is a correlation for initial water level in the Eemskanaal and computation time. However, the inundated area is very small for water levels < 0, and thus the computation time is not affected as much by the number of wet cells.

The results after 24 hours for water levels of -0.5,-0.25, 0, 0.5, 1, and 1.5 hours can be seen in Figure 63.

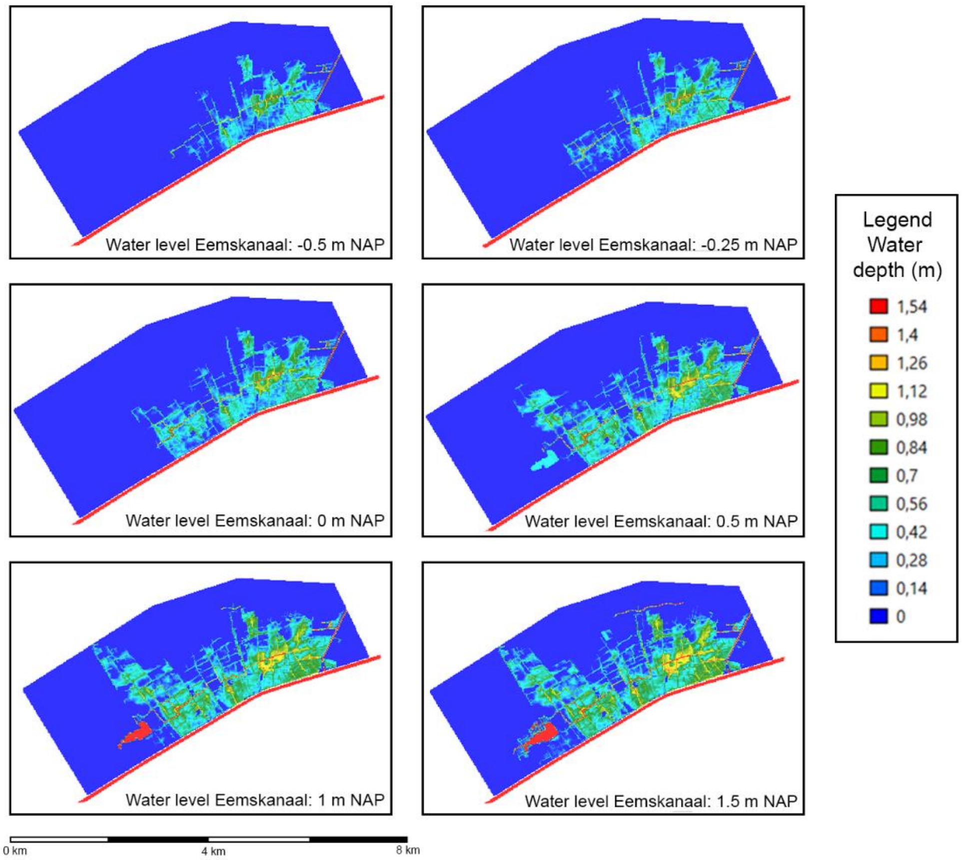


Figure 63: Results after 24 hours for study area 1 with different water levels in the Eemskanaal.

Figure 63 shows that logically the water level has a significant effect on the inundated area. However, the differences are significantly smaller than when a fixed water level was used (Figure 60). This is because with the modelled Eemskanaal, the water level decreases quite rapidly. There is a maximum amount of inflow, determined by the difference in water level between the Eemskanaal and the inundated area. This was not the case with method 2 since water could keep flowing in and the water level in the Eemskanaal would not change. The output in method 3 is definitely a lot more realistic.

Comparing the different methods

From the previous tests, it is clear that all 3 methods provide different outputs. In this test, the 3 methods are compared. This is done based on different characteristics.

Set up

Method 1 and 2 are both very easy to set up. Method 3 however takes a lot more time, and D-HYDRO quite often crashes with multiple grids and interpolations. Also, methods 1 and 2 allow the user for easy modifications to the model. Method 3 does not.

Consistency

Method 1 is the best method to use for consistency. The inflow to the system only depends on the user input, and this way, the user has perfect control over the amount of water entering the system. The inflow in method 2 depends on the bed level, current water level in the system, and the breach size. Breach size is easy to verify and control, however the bed level is not always. Two slightly different models can have a variation in bed level next to the breach, and this can have a significant influence on the total amount of water entering the system. For method 3, the same limitations hold as for method 2. Additionally, the connection in the grid of the Eemskanaal and the inundation area, also can have significant influence on the results. The grid connection is also not as easy to modify.

Realism

Method 3 provides the most realistic scenario. The amount of water in the Eemskanaal, and the flow limitations in the Eemskanaal are both taken into account when determining the breach inflow. Method 2 provides a water level outside the breach. However, in the current release of D-HYDRO, this water level cannot be modified based on the water that has flown through the breach. This is a big disadvantage, since it is difficult to predict the water level over time, since it depends on the inflow. Method 1 requires the user to know the exact breach inflow, which requires separate calculations. This requires additional work, that has to be done before performing the simulation.

Comparing method 2 and method 3

The water level in method 2 does not lower based on the flow through the dike breach. For method 3, it does. Therefore, it is difficult to compare the two. To tackle this problem, first a simulation has been run at a specified water level for method 3. The resulting change in water level over time is saved, and this is used as an input water level for a simulation with method 2. This way, the 2 methods can be compared under more equal circumstances.

In Figure 61, the water level over time for a 20 meter dike breach can be seen. This is the data that is used as an input for the model with a fixed water level. In Figure 64, the results can be seen for the discharge in both the models.

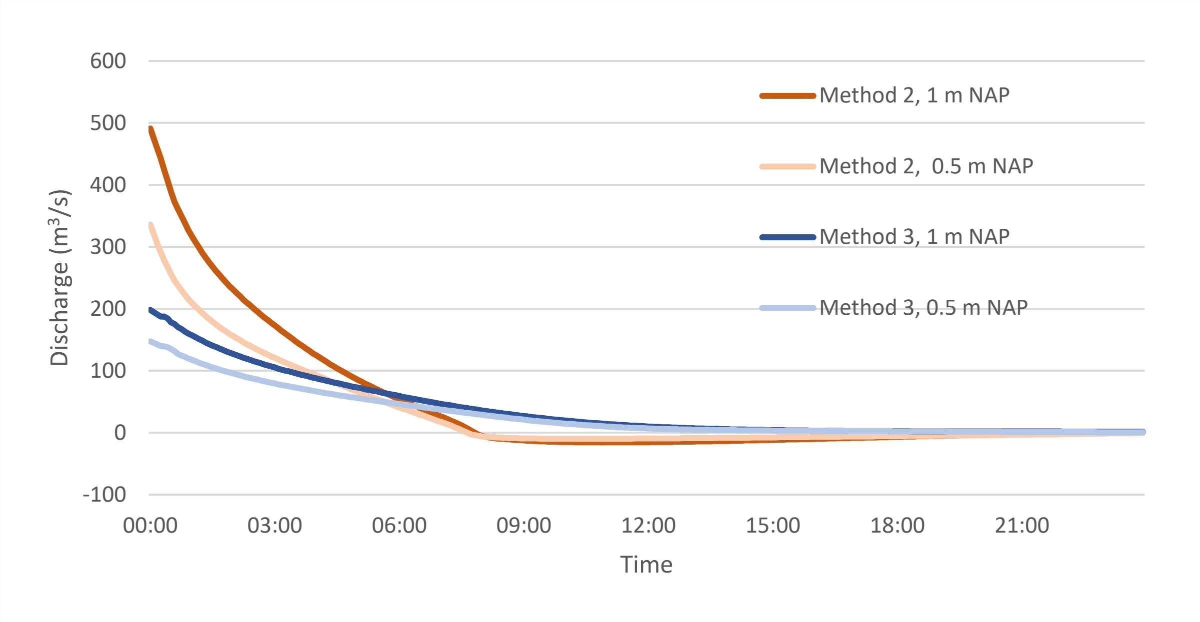


Figure 64: Comparison of the discharge over time between method 2 (predetermined water level at dike breach location) and method 3 (Eemskanaal modelled). The water level changes over time. The water level is determined by simulations with method 3.

Figure 64 shows a striking difference between the two methods. At 00:00, both simulations have an equal circumstances (no water in flood area, and the same water level in the Eemskanaal). It was expected that this would results in similar discharge through the dike breach. However, at the start of the simulation, there already is a 2x difference in discharge through the dike breach. Apparently, modelling the Eemskanaal and connecting the grids results in significantly less water flowing through the dike breach than with an inflow boundary location from method 2. A slight difference in the two methods was expected, but not this big of a difference.

Because the inflow is higher for method 2, later in the simulation, the discharge is negative. This is because the water level is predetermined. With higher discharge, the water level in the inundated area increases more rapidly. After 8 hours, the water level in the inundated area is higher than the water level behind the dike breach. Therefore, water starts flowing back in the Eemskanaal through the dike breach.

Appendix N: Python script for image analysis

The script used to estimate the total amount of water based on an input image. The RGB values in the script have to be modified based on the input image. An example of the input image and the detected water depths can be seen in Figure 65. The script can be seen in Figure 66. All other scripts used in this project are based on a similar concept.

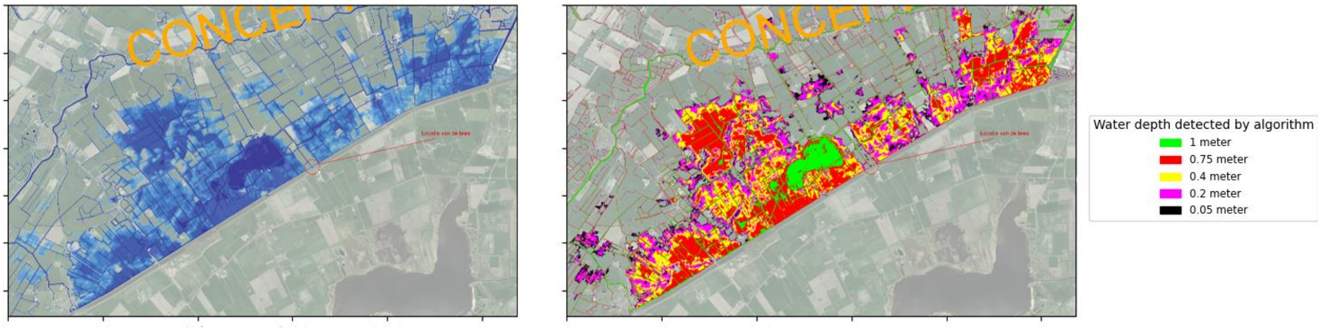


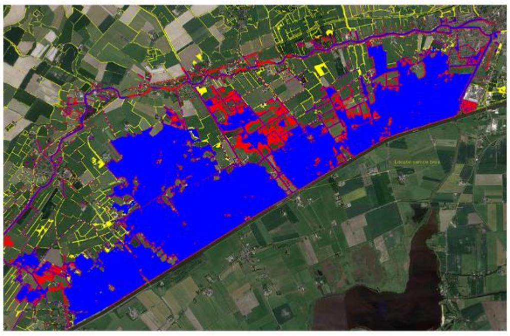
Figure 65: Example of input picture (left) and the water depth read by the script (right).

```python
import numpy as np
from skimage import io, data
from matplotlib import pyplot as plt
import matplotlib.patches as mpatches
import time

# Inputs
LengtUnit = 10000 # fill in lenght in relation to amount of pixels to determine cell size
PixelsInLengthUnit = 11819 # fill in pixels in relation to lengt unit
CellSize = LengtUnit / PixelsInLengthUnit
TotalWater = 0
Cells_1m, Cells_075m, Cells_04m, Cells_02m, Cells_005m = 0, 0, 0, 0, 0
image = io.imread(r"D:\UNI\Stage\DataVorigeOnderzoek\Images from data\Dijkdoorbraak_loc16_Eemskanaal_Hoeksmeer.png")
ImageData = np.array(image.data)

# Check for colors in image, the loop could be more efficient with different if statements
for row in range(ImageData.shape[0]):
    for col in range(ImageData.shape[1]):
        if (50 < ImageData[row, col, 0] < 140 and 50 < ImageData[row,col,1] < 200 and 110 < ImageData[row,col,2] < 240 or
            ImageData[row, col, 0] < 180 and ImageData[row, col, 2] > 200 and 50 < ImageData[row,col,1] < 220 and
            150 < ImageData[row,col,2] < 240):
            if ImageData[row,col,1] < 70:
                ImageData[row,col,0] = 0
                ImageData[row,col,1] = 255
                ImageData[row,col,2] = 0
                Cells_1m  += 1
            elif ImageData[row,col,1] < 120:
                ImageData[row,col,0] = 255
                ImageData[row,col,1] = 0
                ImageData[row,col,2] = 0
                Cells_075m += 1
            elif ImageData[row,col,1] < 145:
                ImageData[row,col,0] = 255
                ImageData[row,col,1] = 255
                ImageData[row,col,2] = 0
                Cells_04m += 1
            elif ImageData[row,col,1] < 185:
                ImageData[row,col,0] = 255
                ImageData[row,col,1] = 0
                ImageData[row,col,2] = 255
                Cells_02m += 1
            else:
                ImageData[row,col,0] = 0
                ImageData[row,col,1] = 0
                ImageData[row,col,2] = 0
                Cells_005m += 1
TotalWater =  (Cells_1m * 1 + Cells_075m * 0.75 + Cells_04m * 0.4 + Cells_02m * 0.2 + Cells_005m * 0.05) * CellSize * CellSize
print("Total amount of water is: " + str(TotalWater))
image2 = ImageData

# Viewing the image, and the original
fig=plt.figure()
fig.add_subplot(1,2,1)
plt.imshow(image)
fig.add_subplot(1,2,2)
plt.imshow(image2)
# Making a legend
LegendColors = [[0,1,0],[1,0,0],[1,1,0],[1,0,1],[0,0,0]]
LegendNames = ["1 meter", "0.75 meter", "0.4 meter", "0.2 meter", "0.05 meter"]
patches = []
for i in range(len(LegendColors)):
    patches.append(mpatches.Patch(color = LegendColors[i], label = LegendNames[i]))
fig.legend(handles = patches, title = "Water depth detected by algorithm", fontsize = 'small')
plt.show()
```

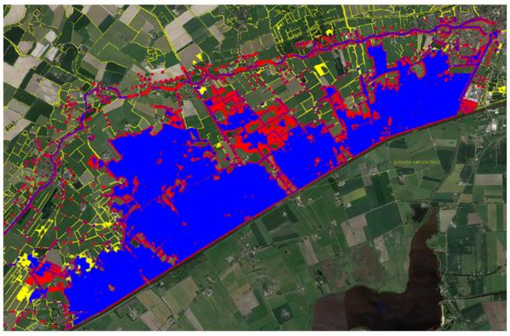
Figure 66: Python script that has been made to estimate total amount of water based on input picture (script varies per input picture, since different colour scales are used).

Appendix O: Hoeksmeer

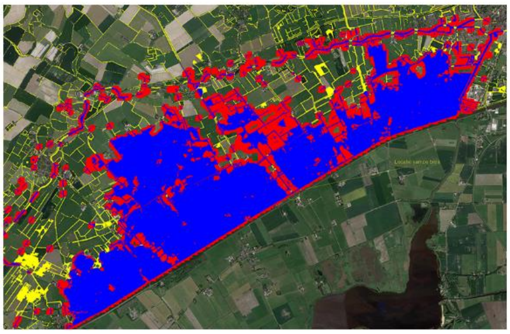
10 meter resolution, water depth after 4 days



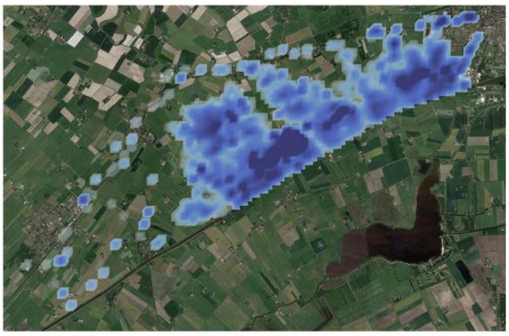
20 meter resolution, water depth after 4 days

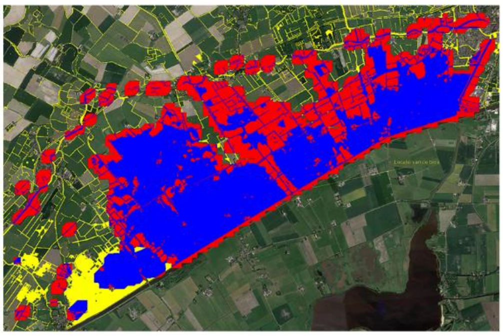


50 meter resolution, water depth after 4 days



100 meter resolution water depth after 4 days





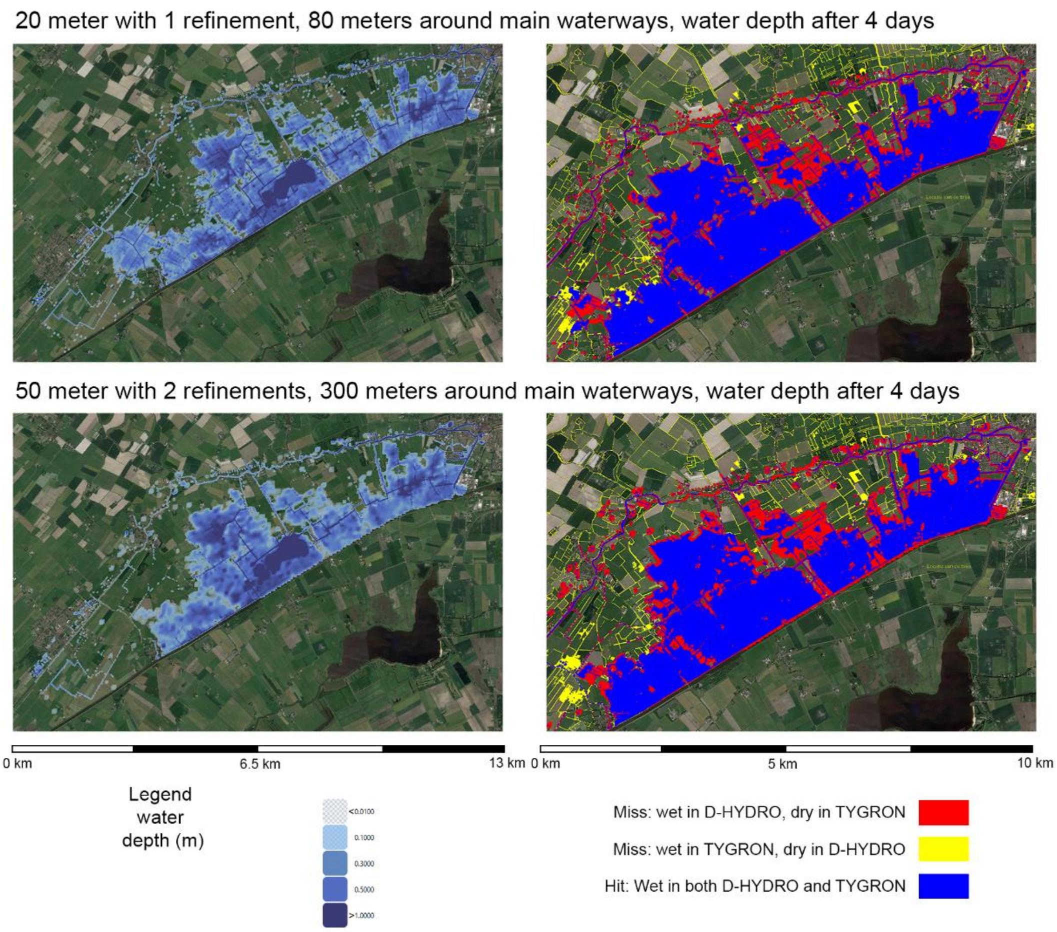
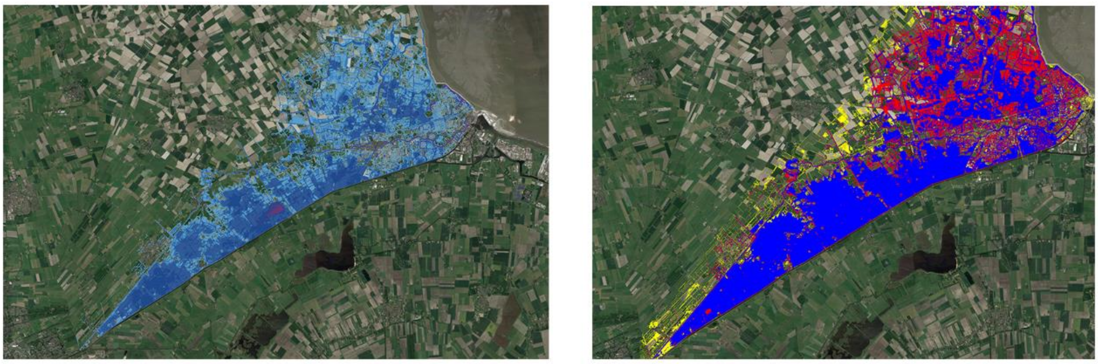


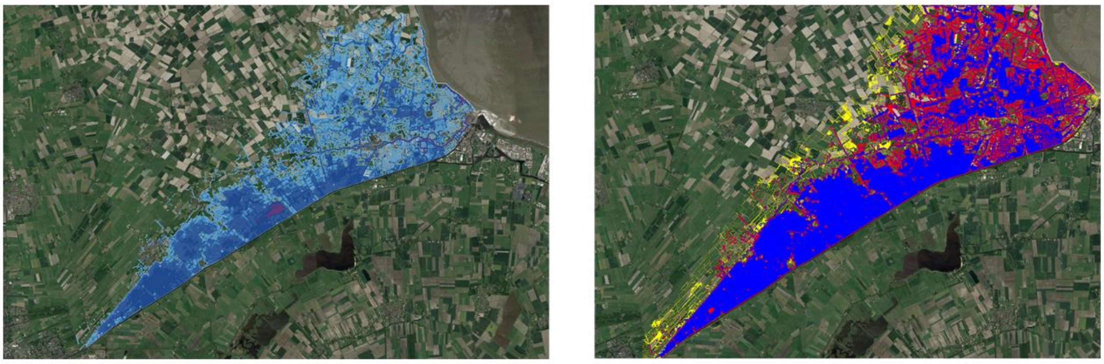
Figure 67: All results for simulations in D-HYDRO at dike breach location 1: Hoeksmeer.

Appendix P: Delfzijl

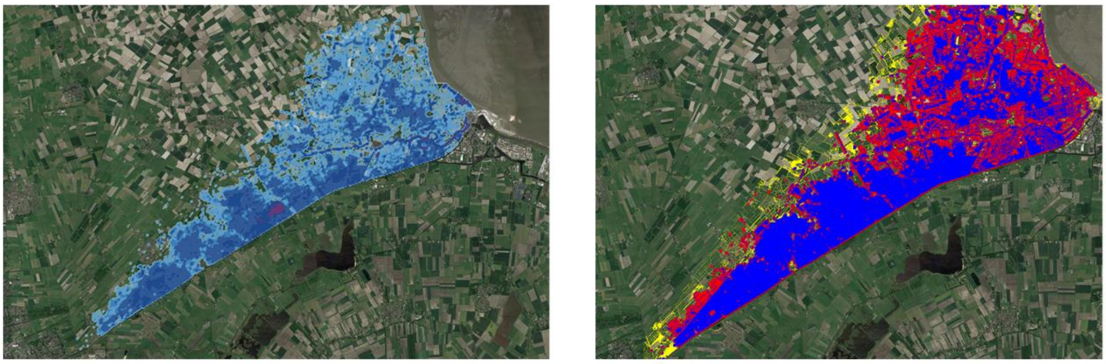
10 meter resolution, water depth after 4 days



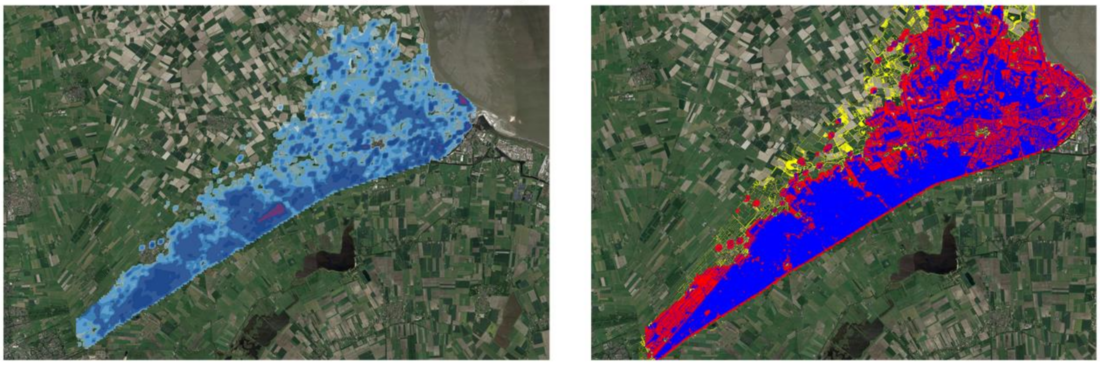
20 meter resolution, water depth after 4 days



50 meter resolution, water depth after 4 days



100 meter resolution, water depth after 4 days



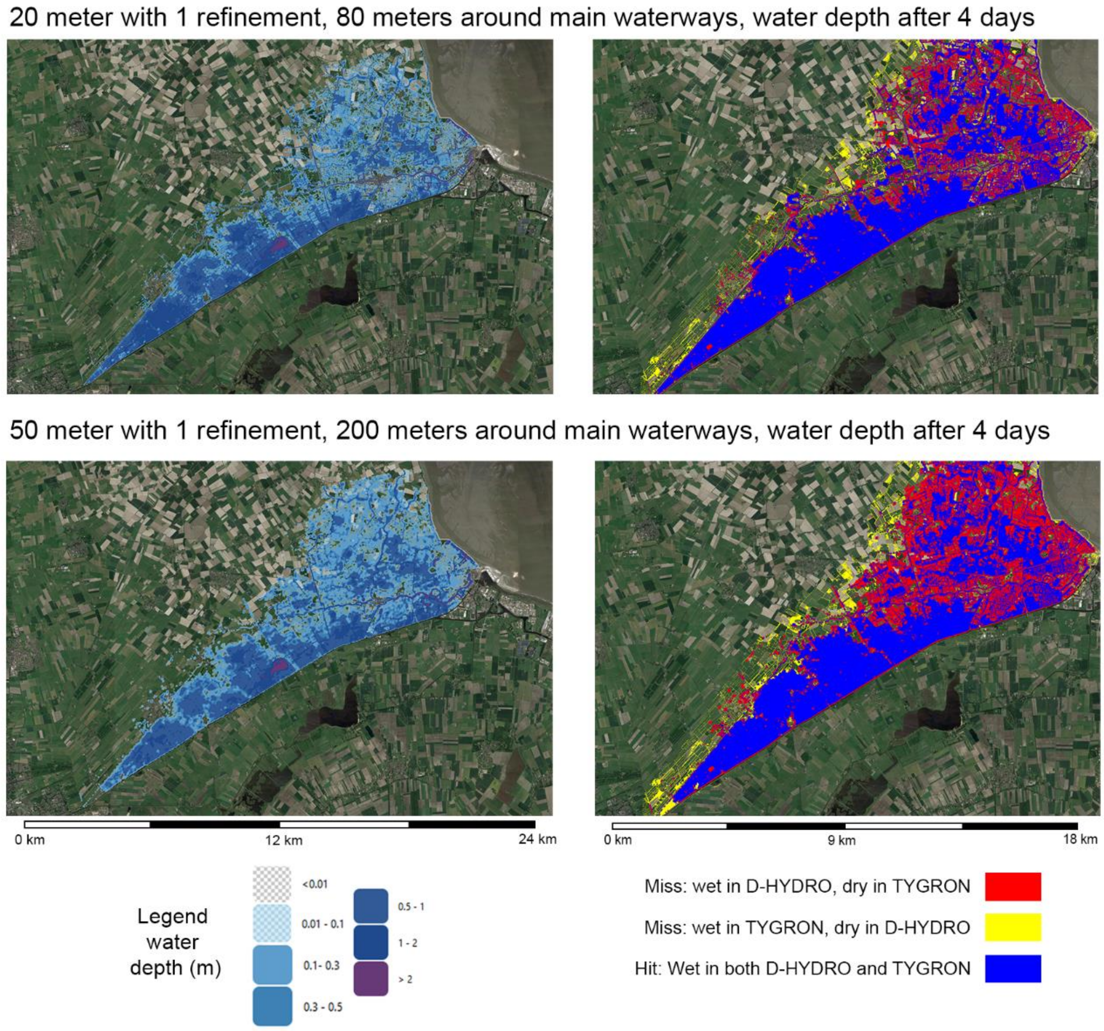
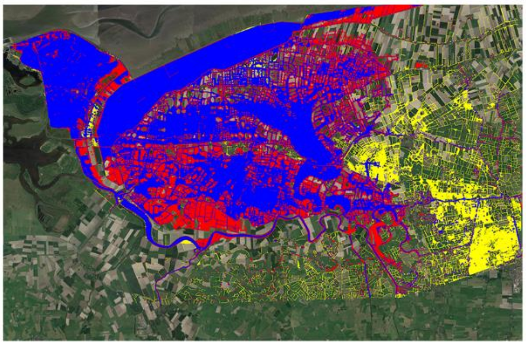


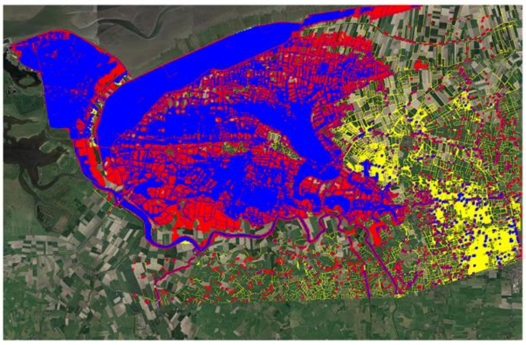
Figure 68: All results for simulations in D-HYDRO at dike breach location 2: Delfzijl.

Appendix Q: Deikum

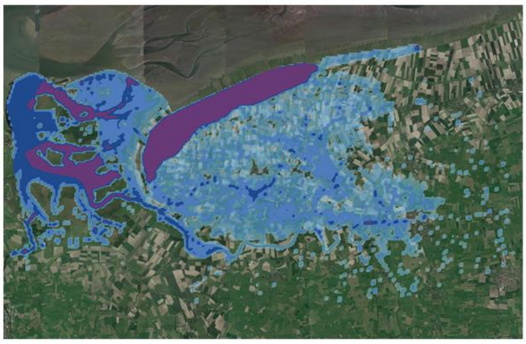
20 meter resolution, water depth after 4 days

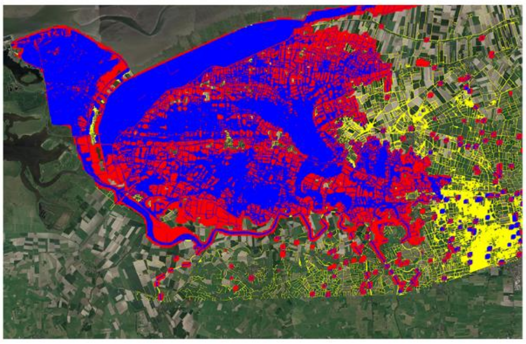


50 meter resolution, water depth after 4 days

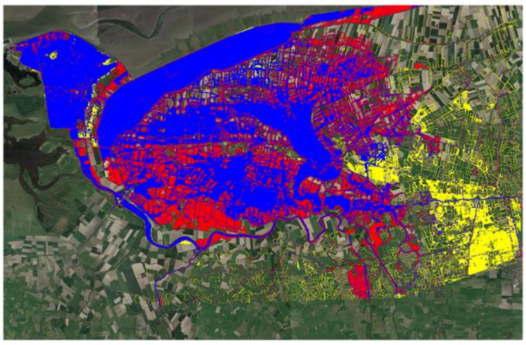


100 meter resolution, water depth after 4 days





20 meter resolution,with 1 refinement, 80 meters around main waterways. Water depth after 4 days



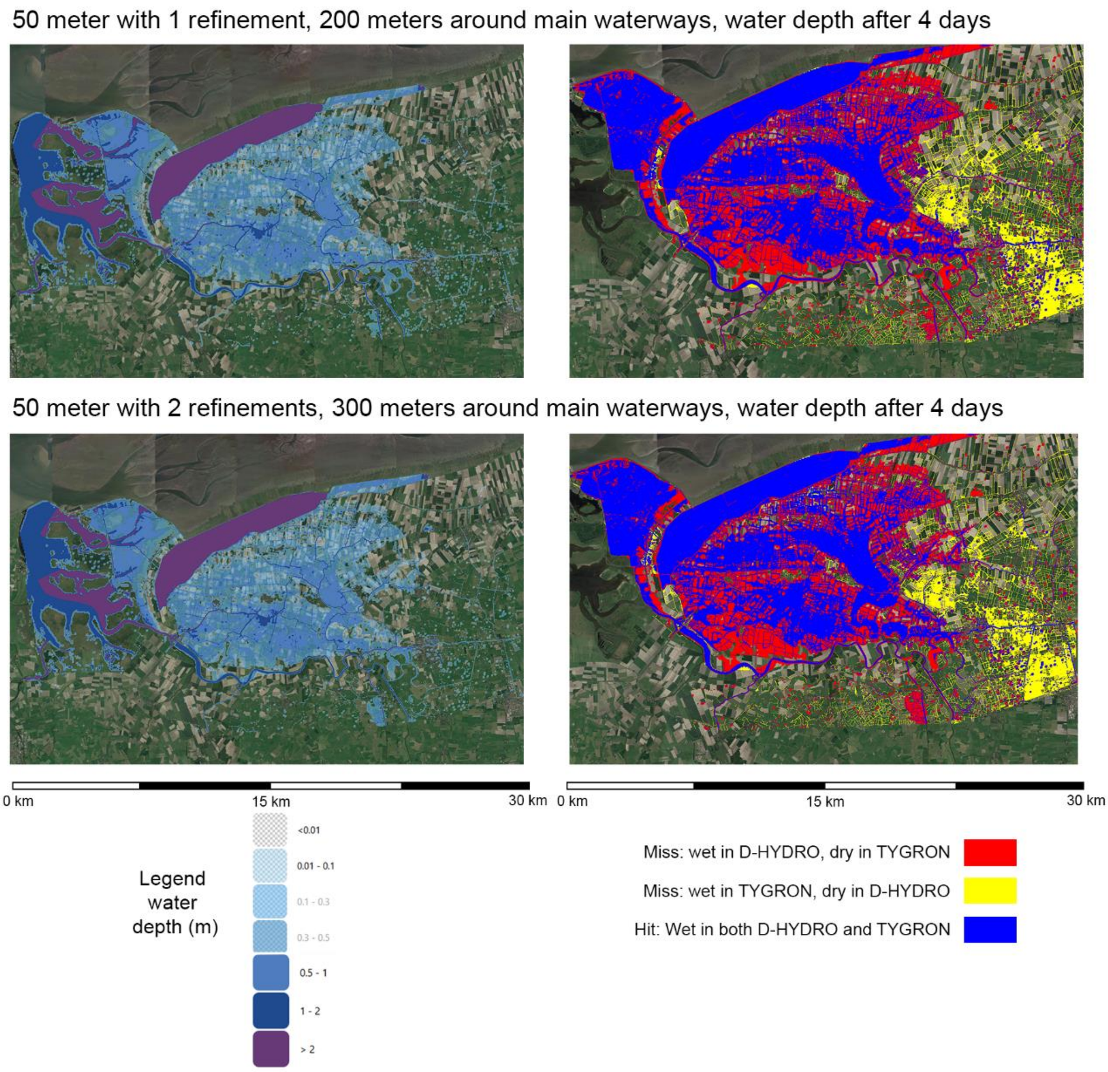


Figure 69: All results for simulations in D-HYDRO at dike breach location 3: Deikum.

Appendix R: List of bugs/advise for D-HYDRO (version 0.9.7, January 2021)

Bugs

- When you fill in a value in the general simulation settings, the input you give disappears when you go to another tab without clicking in another field first.
- With a flexible mesh model, interpolating the .xyz files onto the grid causes weird lines. This can be prevented by going to the grid and using “merge duplicate vertices” and “orthogonalization” (I do not know why this works, figured it out by a lot of trial and error). However, after saving the file and opening it again, the weird lines do often return. This issue has been reproduced by Deltares.
- 1D2D coupling does not work when you construct a 1D model in D-HYDRO. Deltares mentioned that they have mainly focussed on 1D models imported from SOBEK.
- In the beta version 0.9.6.5.51435, importing initial water levels from a .xyz file did not work. This is fixed in the 0.9.7 release.
- When trying to model multiple separate grids, D-HYDRO crashed often and was really slow.
- For some of the GIS to 2D importers, for example fixed weirs, the imported feature lines or polygons cannot contain values. Therefore, all heights have to be added manually. This can be a lot of work.
- With really big models (many grid cells), the results in the GUI after running the model have many white pixels that overlay the results.

Advice

- When exporting an image based on results, the image that is saved is based on the current zoom level in the GUI. This should be taken into account. If you want to compare different images, make sure you have the same zoom level in the GUI. This can be done by using “zoom to location” on a specific layer.
- When trying to find a size of the buffer for flexible mesh, check if every part that needs to be refined is actually refined. This can vary based on the location. As a basis, use the following numbers: for 1 refinement with a 20*20 grid, use a 80 meter buffer around waterways. For 50*50 grid with 1 refinement, use a 200 meter buffer. For 50*50 with 2 refinements, use a 300 meter buffer.
- Take note that when using flexible mesh, adding refinements next to the breach location costs additional computation time. See Appendix G: Courant numbers to read more about why this should not be done.
- Big .xyz input files cause D-HYDRO to run slowly and freeze. Often by just waiting the problem resolves. A progress bar would be nice. In general, when D-HYDRO seems to crash, just wait and most often it will work out.
- Do not import files form a separate hard drive, this slows the importing, which is logical.
- Saving and opening large models can take a long time.
- When you model a period of for example: 00:00:00 01-01-2021 to 00:00:00 02-01-2021 with all settings on default, the results are outputted for the time period: 01:00:00 01-01-2021 to 01:00:00 02-01-2021. This is due to the time zone. Change the time zone to 1 to fix this. This can be done in the general settings.
- When you run and save a model, in directory search for this file: *“..\model\model.dsproj_data\FM_model_output\dflowfm\DFM_OUTPUT_FM_model\FM_model*

_map.nc" This file can be loaded in QGIS to get a good visualisation of results. This was not known during the first 5 weeks of the research, however, can be very helpful.

- Make sure your computer does not go in standby during a simulation. Either change windows settings, play a video, or use the program caffeine.exe to keep the computer on.
- It is advised to use QGIS to to easily convert .tif files (DEM, roughness, water level) to .xyz files, which are required for D-HYDRO. After creating a .xyz file, the no data values have to be removed. There are no data values since the input .tif map is most likely not a rectangle. Converting a cut out .tif file to a .xyz map creates a rectangle around the map (in order to ensure a rectangle output), with no data values on locations that were not in the original map. These no data values can be removed using a command in windows:
  [findstr /V "e+" "input_file_location"> "output_file_locaiton"]
  With input and output files being .csv or .xyz files.
- When using a boundary condition, lay the boundary close to the grid. When a boundary is added, the model checks to which grid cells the boundary is "connected". And it connects the boundary condition to the borders of these grid cells. The exact size of the boundary does not matter. It only matters which grid cell edges the boundary is connected to.
- The default initial water level is 0. When your modelled area is under NAP, it will be inundated from the start. You should lower the default initial water level in this case.

Suggested modifications to database Noorderzijlvest

- Weirs are mapped as point features. Currently it is not possible to import point features for a 2D model. It would be better if they were mapped as line features.
- Make a DEM map that has data values for all waterbodies and buildings. I also made such a map for the entire area. However, I suggest someone from the waterboard makes one, so someone from the waterboard knows the workflow for this.
- Make a map of the roughness values of the area. This can be done with the LGN7 map. I again advise someone from the waterboard makes this map to understand the workflow.
- Make a map of the water levels of the area, this can be done using the map "peilgebieden". I again advise someone from the waterboard to make this map to understand the workflow.
- Make a map of the dikes in the area, also include smaller dikes. For simulations with big grid sizes, including dikes can help improve the accuracy of the simulation significantly.
  I suggest waiting until D-HYDRO allows for crest levels to be imported. Because then it can be checked what input is required, and the map can be made accordingly.